RECEIVER DESIGN FOR A SHORT RANGE, PRECISE, NAVIGATION SYSTEM

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by

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ABSTRACT

A precise navigation system has been proposed for use in mine and amphibious warfare. It is a continuous-wave phase comparison system, which derives its information from the change in phase between two stable oscillators as the distance between them is varied. A receiver, with very good phase versus temperature stability, was designed for this system. A test circuit was designed to field monitor any receiver phase changes which do occur. A method to frequency lock several oscillators to a master was also devised. Tests were run to determine the stability of the receiver, and the feasibility of the system.

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ACKNOWLEDGEMENT

Mr. Hollis W. Oren of the Naval Postgraduate School Research staff has been of invaluable assistance in building the receiver discussed in this paper. His ideas were always welcomed, and both thought provoking and useful. His practical experience and knowledge were not only extremely helpful, but also an education of priceless value.

1. Introduction.

Mine warfare, and its closely allied operations of amphibious assault and harbour security, require both precise, and, hopefully, passive navigation. The accuracies of both mine laying and mine sweeping are obviously limited by the navigation system, while amphibious assault, the most complex military operation yet conceived, requires accurate navigation for both timing and control. The passive feature is desirable not only from the standpoint of ECM, but also for the reduction in the already overcrowded military communication nets. At the present time Radar, Loran, Omega, or even visual methods are unable to accomplish this simultaneously.

The system discussed in this paper was first proposed in Lieutenant J. G. Dean's thesis[(1)] on the investigation of frequency stability in a short-range, precise navigation system. It involves the phase comparison of two signals of the same frequency; one received from a CW transmitter in a known location, the other at a shipboard receiver. Under ideal conditions the only phase change will be due to the relative motion between the transmitter and the receiver. Further discussion of the system theory will be delayed until the next section.

The problem, however, is that ideal conditions are seldom achieved. The limiting factor in this system is obviously the stability of the two oscillators. It is not necessary that they both be equal to a certain frequency F_c, but that they both equal each other and be in the neighborhood of F_c. In other words, both oscillators must be well matched in both frequency and drift rate. Oscillators are now available with frequency drift rates of a few parts in 10^{10} or 10^{11} per day. This problem was the subject of Lieutenant D. R. Austin's thesis[(2)], and was also well discussed by Dean.

With this as the limiting factor, other possible sources of error must be studied and either eliminated or circumvented. The three obvious problems are phase stability of the transmitter and receiver, propagation effects, and possible variations in the positions of the transmitter. The first problem must, of course, be solved before the other two may be properly considered. This was the main area studied in this paper.

The phase stability problem of the transmitter was solved by using a VCO feedback arrangement, phase locked to the master oscillator. Attempts were made in the design of the receiver to develop a satisfactory narrow pass filter with a flat phase versus frequency characteristic. It was found, however, that at the frequencies being considered, this involved a great deal more complexity and expense than was desired. Since, therefore, the problem could not be eliminated readily, an attempt was made to circumvent it with a test circuit which will give the instantaneous phase shift of the receiver itself.

Because of the phase problem the number of filtering stages was kept to a minimum, and with it there was a necessary reduction in signal sensitivity and selectivity. It is hoped that with the success of the test circuit, more filtering and amplification will be possible, and hence a more finely tuned receiver.

The final tests indicated an acceptable degree of receiver stability, and that the test system was a satisfactory method of coping with the minor changes. They also emphasized the fact that the oscillators are the limiting factor. The ones used in this study proved to be within reasonable standards for only short periods of time. Possible errors of 20 meters can be expected in less than four hours of operating time. This may be more than satisfactory for some applications; for others improved oscillators will be necessary.

The next section, and the two following on the oscillators and the transmitter, were discussed in Dean's thesis, and are included here as background material.

2. A Review of the Navigation System Concept.

While the system is not necessarily restricted to shipboard use, nor the transmitter to a buoy, it will be assumed here to be a completely water borne unit. Complete propagation over water is desirable for the constant dielectric and conductivity constants, and straight line propagation paths. Ranges of from one to fifty miles are envisioned with accuracies independent of distance. Although the strictly ranging properties of this system will normally require at least three transmitters for an unambiguous fix, only one transmitter operation will be considered in this paper (figure 2.1). While a method of slaving two to a master third will be discussed later, the concepts are identical in all other respects. The concentric arcs in figure 2.1 represent points of equal phase, and hence equal range.

Assume two oscillators with the same frequency and phase. Identical phase is not important, but it makes the theory easier to understand. If these two oscillators were physically occupying the same place, an observer could detect no difference between them. However, if they were physically separated by one half wave length, and the signal at #1 was transmitted to #2, and then compared, they would appear to be 180° out of phase. The oscillators themselves are still in phase, but now there is a delay of one half period due to the finite speed of transmission (327.838 yards per microsecond in a vacuum). At the frequency used in this study, 2.0 MHz, one wave length -- 360° phase shift -- is equal to 163.92 yards, 150.0 meters, or a time lapse of 0.5 microseconds.

By starting, therefore, with the receiver oscillator at a known position (point A, figure 2.1), a phase difference can be measured with respect to the transmitter oscillator. Then any distance traveled from this position, relative to the transmitter position, will be directly

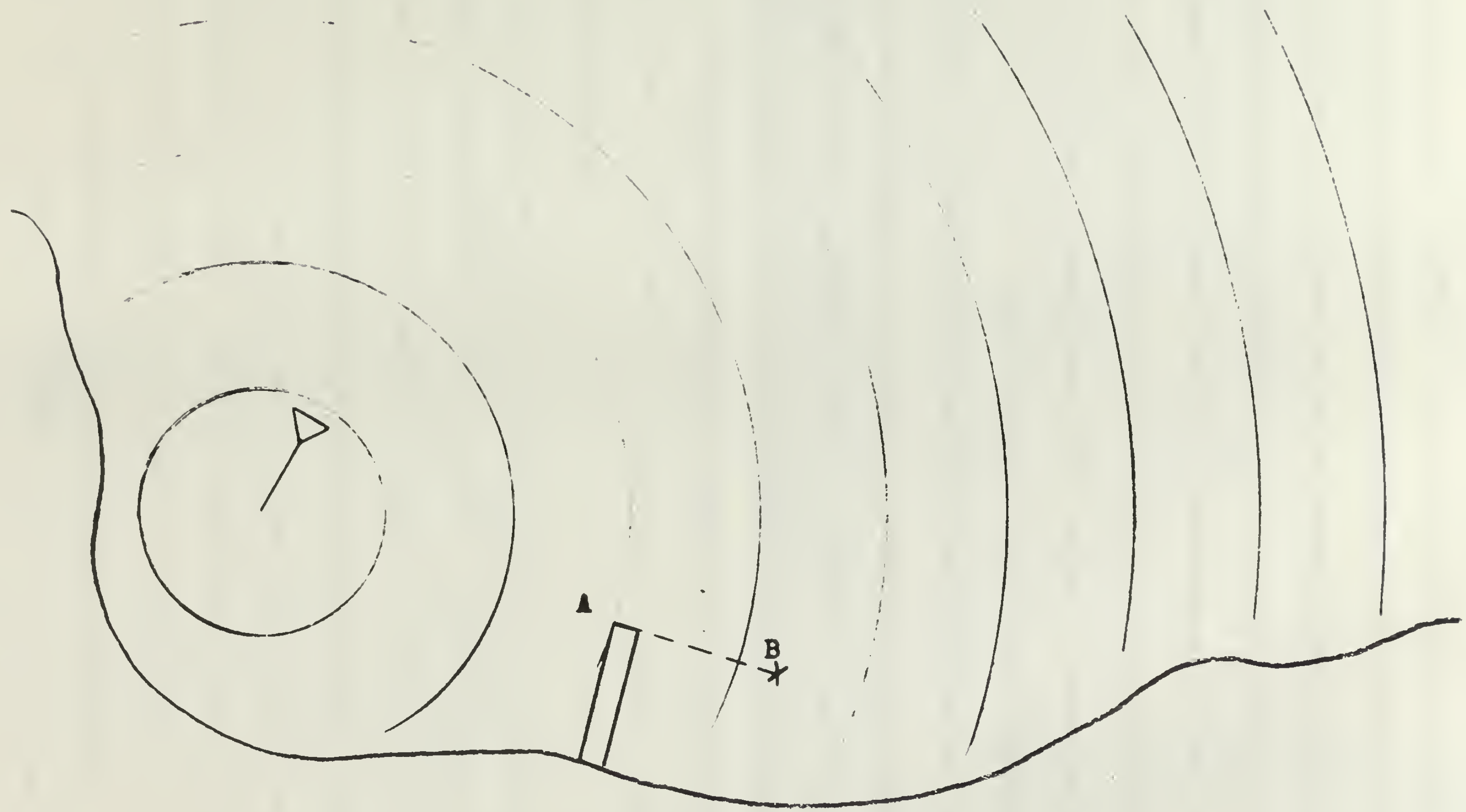


Figure 2.1. The Basic Ranging System

related to the phase change. As an example, in traveling from point A out to point B, there has been an elapsed phase change of +1.25 cycles -- 450°, or 0.625 microseconds at 2.0 MHz -- which is equal to 204.90 yards (187.50 meters) away from the transmitter. Note that this result would be the same anywhere on an arc through B, centered on the transmitter. A veeder counter, and a calibrated meter could be used to indicate the total elapsed number of cycles; these could obviously be read out directly in yards, if desired. Any system errors will appear only in the determination of part of a wave length; the number of wave lengths, or gross range, has no effect on this.

Also covered later in the paper will be a possible method of adjusting the receiver frequency to that of the transmitter at the commencement of the run. Once the run is in progress, the oscillators are independent and must remain frequency stable for the duration. This problem is the subject of the next section on the oscillators.

3. The Oscillators.

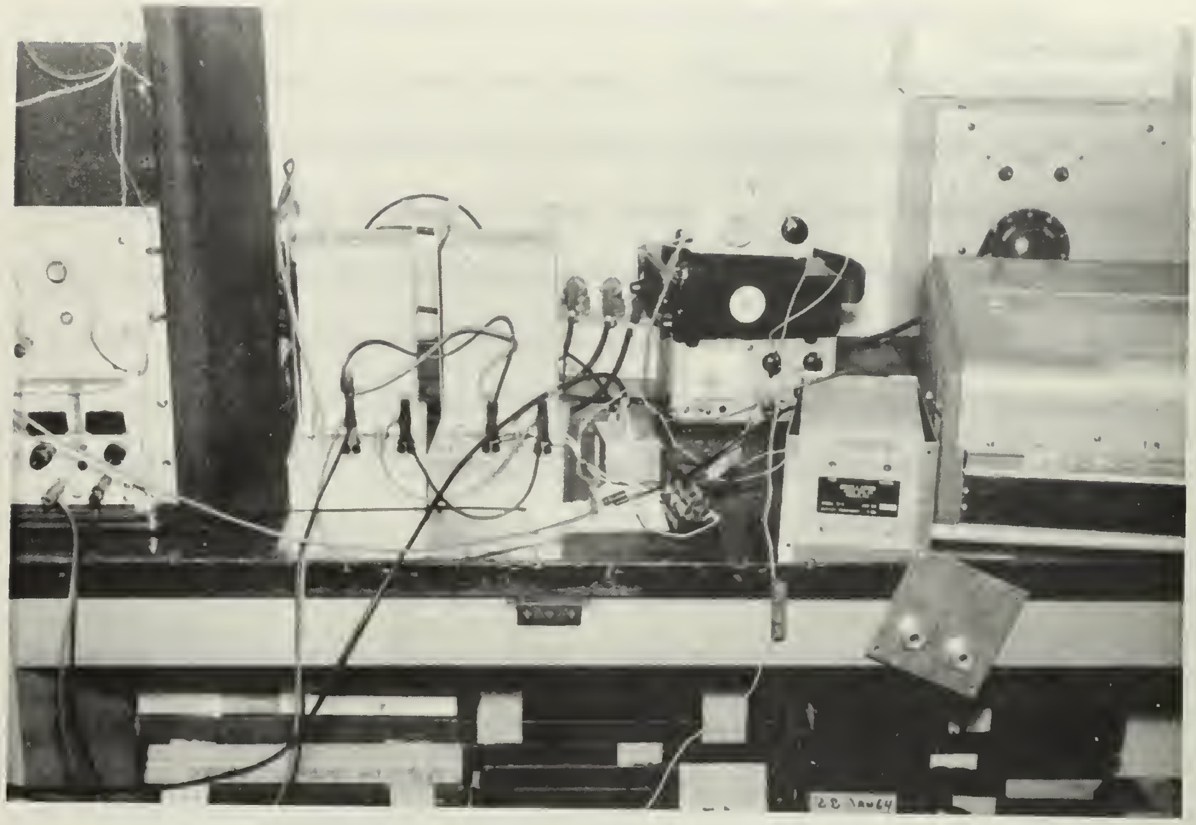
The oscillators available for this system were three Sulzer Laboratories' Model D5 units[3]. These are solid state crystal oscillators which produce a 5.0 MHz, 1.0 volt, sine wave into a 50 ohm load. The crystal, an AT-cut quartz plate, operates in the fifth overtone, thickness-shear mode; it is temperature stabilized in a double proportional oven. They are well packaged in an aluminum container 4.25" x 4.25" x 6.875", and weigh three and one-half pounds.

At the time of this investigation the drift rates of the oscillators had settled down to the order of one part in 10^{10} per day. This is after almost constant operation since 23 July 1965.

Stringent stability and shock tests were made by Austen on these oscillators, and followed up by Dean's further analysis. The reader is referred to these two authors and the manual for more information.

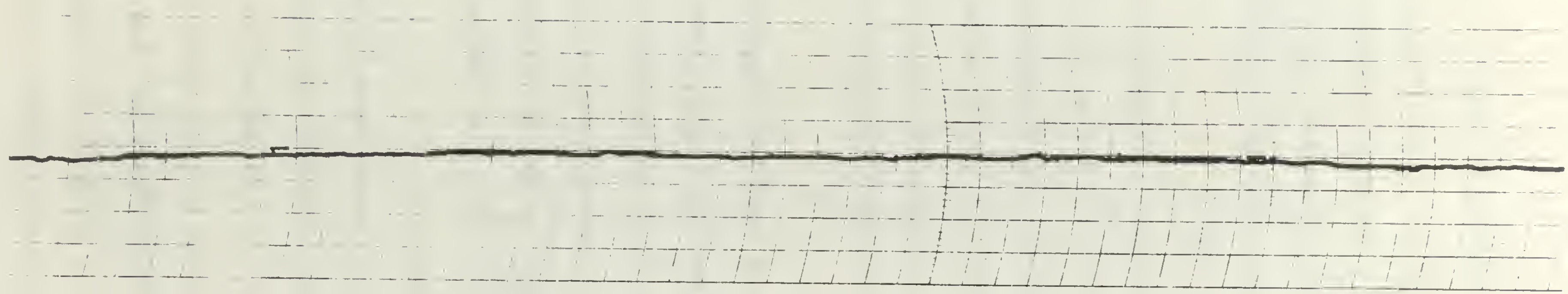
Of importance to this paper are the comparison tests run between two oscillators, and the use of the varicaps to frequency lock one to another electrically.

The initial tests run by Austin and Dean were set up to be run at 100 KHz; a division by 50 of all factors. This was done to facilitate comparison tests with the standards equipment available, however, it tends to make comparison tests of the two oscillators deceiving. An example is figure 3.2; the 24 hour plot of the phase difference of two independent oscillators at 100 KHz. This is a normal plot of the oscillators, once they have been brought into alignment. What appears to be a total error of 18°, is equivalent to 900° at 5 MHz, and a system error of 360° at 2 MHz. But it should be noted that these are all the same absolute error, since degrees are relative at only one frequency. One often sees phase referred to in terms of an absolute time standard when interfrequency



Sulzer Model D5 Oscillators

Figure 3.1



Scale: 1 cm/hr

360° full scale deflection (9°/unit)

24 hour Phase Comparison Run; Oscillator #1 versus Oscillator #3

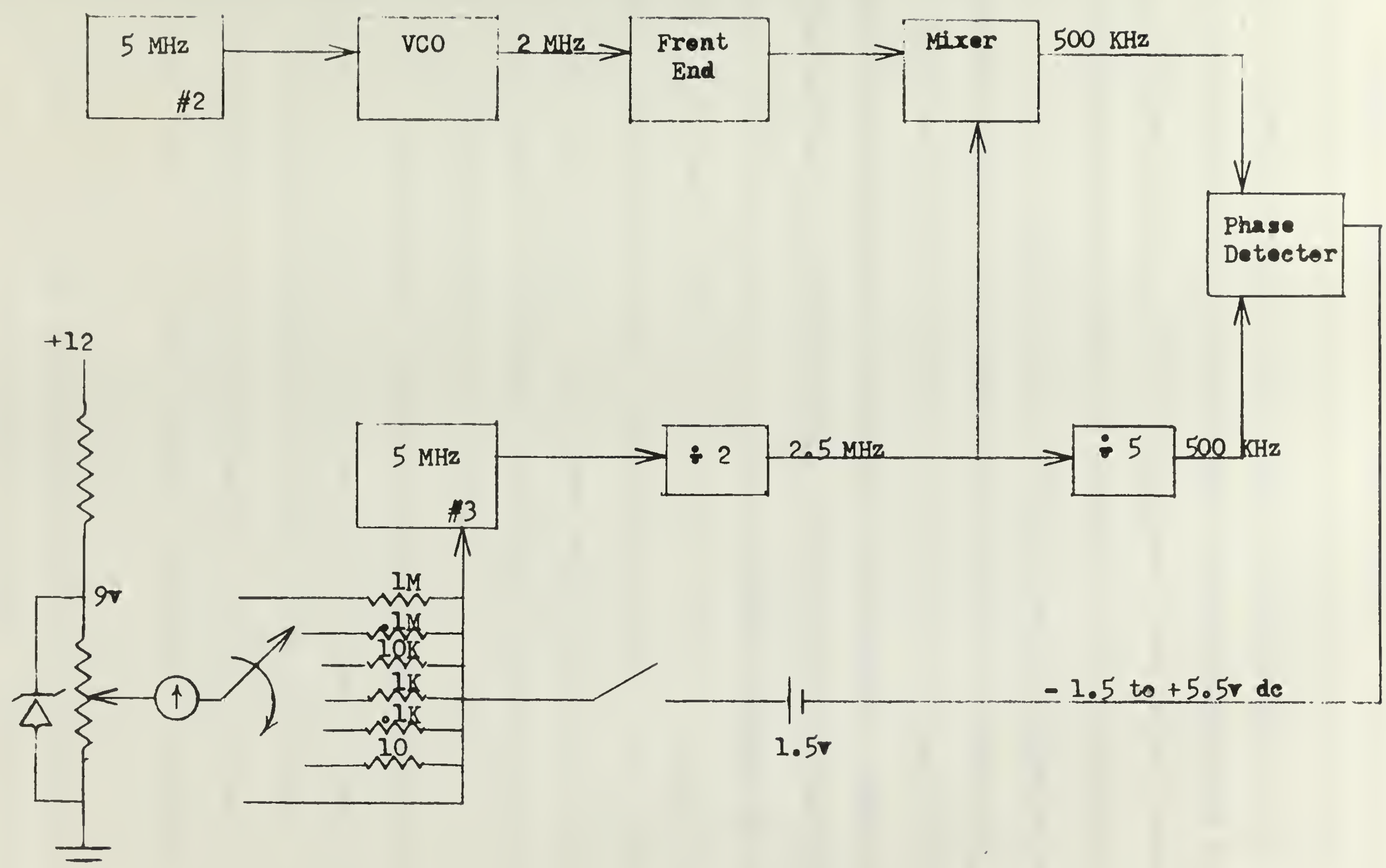
Figure 3.2

comparison is desired. The conversion is simple: x degrees phase shift, at frequency F, equals (x/360)(1/F). In the above case 18° at 100 KHz equals 0.5 usec., while 360° at 2 MHz also equals 0.5 usec. Distance errors are then equal to (0.5 usec.)(speed of light - 300 m/usec.), which equals 150 meters. A final phase comparison test, run at 2 MHz, through the entire system is discussed later.

Nevertheless 150 meters is not acceptable, even though the oscillators do appear to drift at near equal rates, and in the same direction. There are two possible alternatives: either more stable, and more expensive, atomic standards may be used, or the system must be used for a shorter period of time before realigning the local oscillator. One must then, of course, be able to do this rapidly; complete manual tuning often requires 2 - 3 days.

It is with this problem of frequency aligning the oscillators in mind that the use of their varicaps was investigated. Sulzer specifies a possible frequency adjustment of approximately 35×10^{-9} over a range of from one to seven volts dc. This would mean that once two oscillators are within this range of separation one may be electrically slaved to the other. Both a coarse (800×10^{-9}) and a fine (100×10^{-9}) mechanical tuning system are also available.

It was found that the oscillators could be servoed electrically. While the tests will be discussed in section six, figure 3.3 shows the block diagram of the method used. A 1.5v battery was necessary to shift the feedback level from the -1.5v to 5.5v dc output of the phase detector to the 0 - 7v dc required by the oscillator varicaps. A microammeter and multi-turn pot arrangement, as shown in the figure, was designed to hold the oscillator on frequency for independent service. The resistors both isolate the voltage source from the feedback loop, and produce



Block Diagram of Receiver, and Frequency Lock Arrangement

Figure 3.3

current for the meter. With the switch in the 1M position the potentiometer is varied until the microammeter, used here as a null-meter, reads zero. This is done at each switch position until the potentiometer voltage exactly equals that fed back to the oscillator; opening the feedback loop then should not effect the slave, which should continue to run independently at the same frequency. In this way the two oscillators can be aligned in a matter of minutes. It should be noted, of course, that the potentiometer supply must be well regulated.

This ability to electrically frequency slave the oscillators could then be applied as the basis of a multi-transmitter servoed system. Such a system, which is discussed in the appendix, would make it economically feasible to use an atomic standard as a master, with several less expensive slaves.

4. The Transmitter.

The system transmitter -- figure 4.1 -- is a 2.0 MHz voltage controlled oscillator, with phase stability provided by a 5.0 MHz Sulzer model D5 oscillator. The 2.0 MHz signal was chosen not only for its desirable location in the frequency spectrum, but also because it is easily obtainable from the 5.0 MHz standard.

The physical advantages of 2.0 MHz* are its location at the upper end of the Medium Frequency band, its reasonable wave length, and the possibility to still use a physically short antenna on the buoy transmitters. 2.0 MHz is located at the upper end of an assigned marine navigation band and just above the AM broadcast band; at these frequencies stable ground waves should be expected for the range of the system, 30 to 50 miles. The wave length, which is also the distance between ambiguities, of 2.0 MHz is 150 meters; this is long enough so that the ambiguities may be easily dealt with at normal ships speeds, and still short enough to allow for desired accuracy. The antenna lengths must also be considered if buoy mounting is to be feasible; a frequency much lower than 2.0 MHz will pose efficiency problems when loading a short antenna.

The VCO arrangement allows for absolute phase control, and also the possibility of using other frequencies if necessary or desirable. Dean, in his thesis, recommended the removal of the VCO because of its extreme sensitivity to shock and temperature. However, it was found that a very slight modification improved its stability a great deal.

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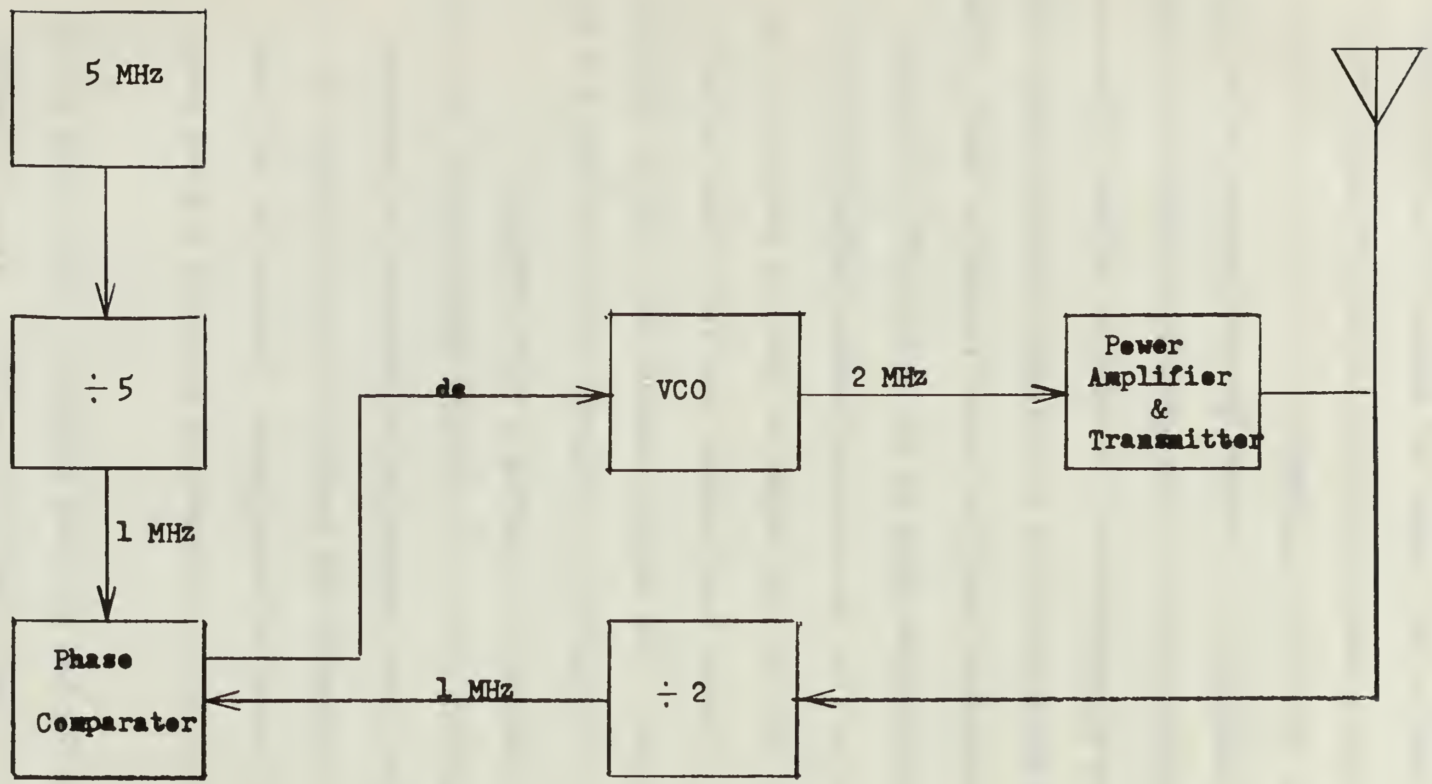
*This frequency of 2.0 MHz has not been assigned to the system and is intended for use only in bench feasibility studies. Final frequency allocation, however, is recommended in this region.



Transmitter Block Diagram

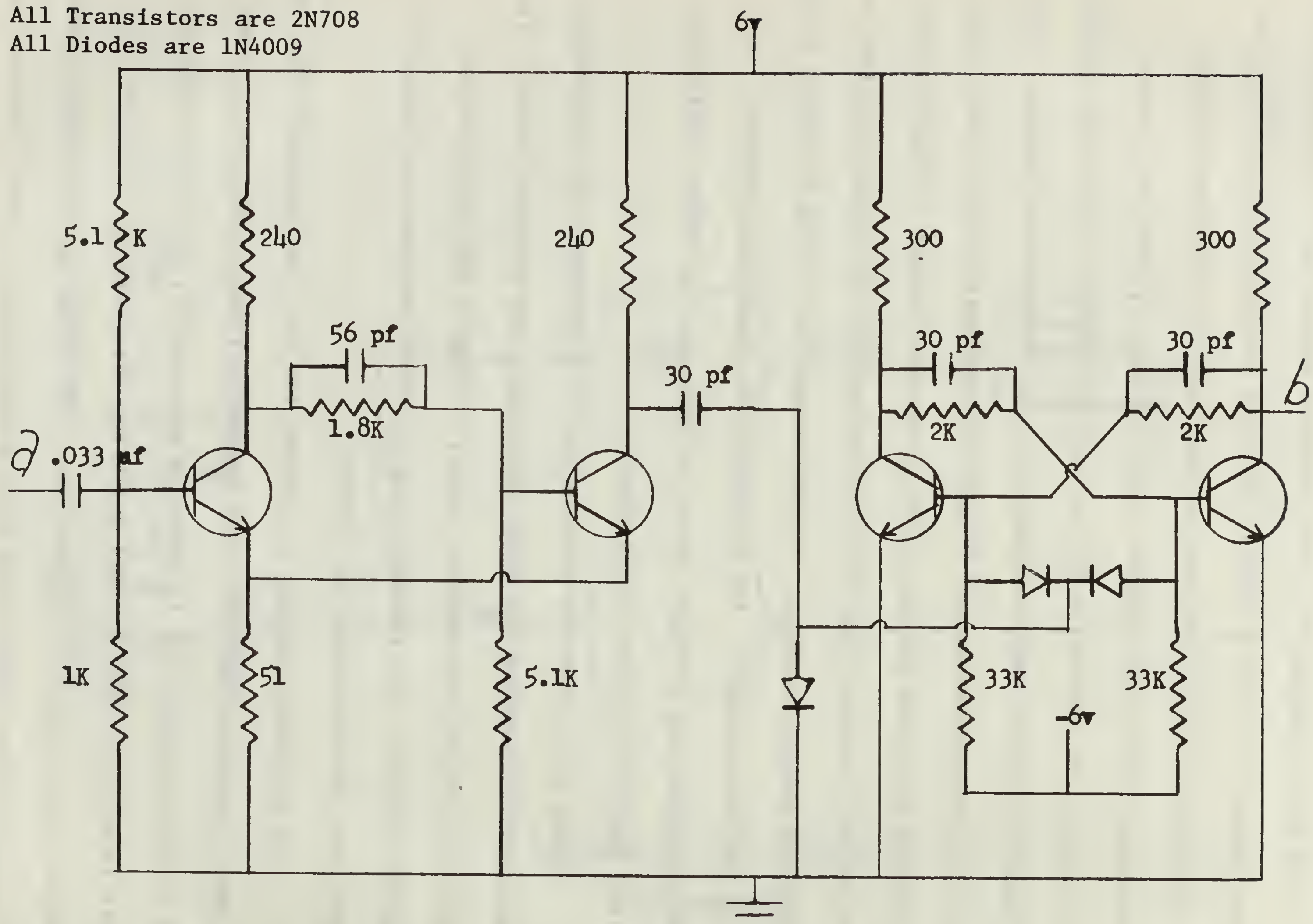
Figure 4.1

It still proved to be somewhat sensitive to temperature changes, but proper packaging, and its normal water cooled environment, should eliminate this problem.

The block diagram shows the feedback system used to achieve the necessary phase stability. This is also the identical system, less the power amplifier, used as the receiver test circuit mentioned earlier, and discussed in the next section. The VCO is a 2.0 MHz oscillator whose frequency is controlled by two varactor diodes in the tank circuit. This signal is fed to the power amplifier and transmitter stages. A portion of the transmitted signal is inductively coupled off of the antenna base loading coil, and fed into a divide-by-two circuit. The resulting 1.0 MHz signal is phase compared with another 1.0 MHz signal obtained by dividing the Sulzer oscillator 5.0 MHz output by 5. The dc output is fed back to the VCO varicaps. Any difference in phase then produces a dc output such that the varicaps alter the frequency an amount sufficient to bring the VCO back into equal phase.

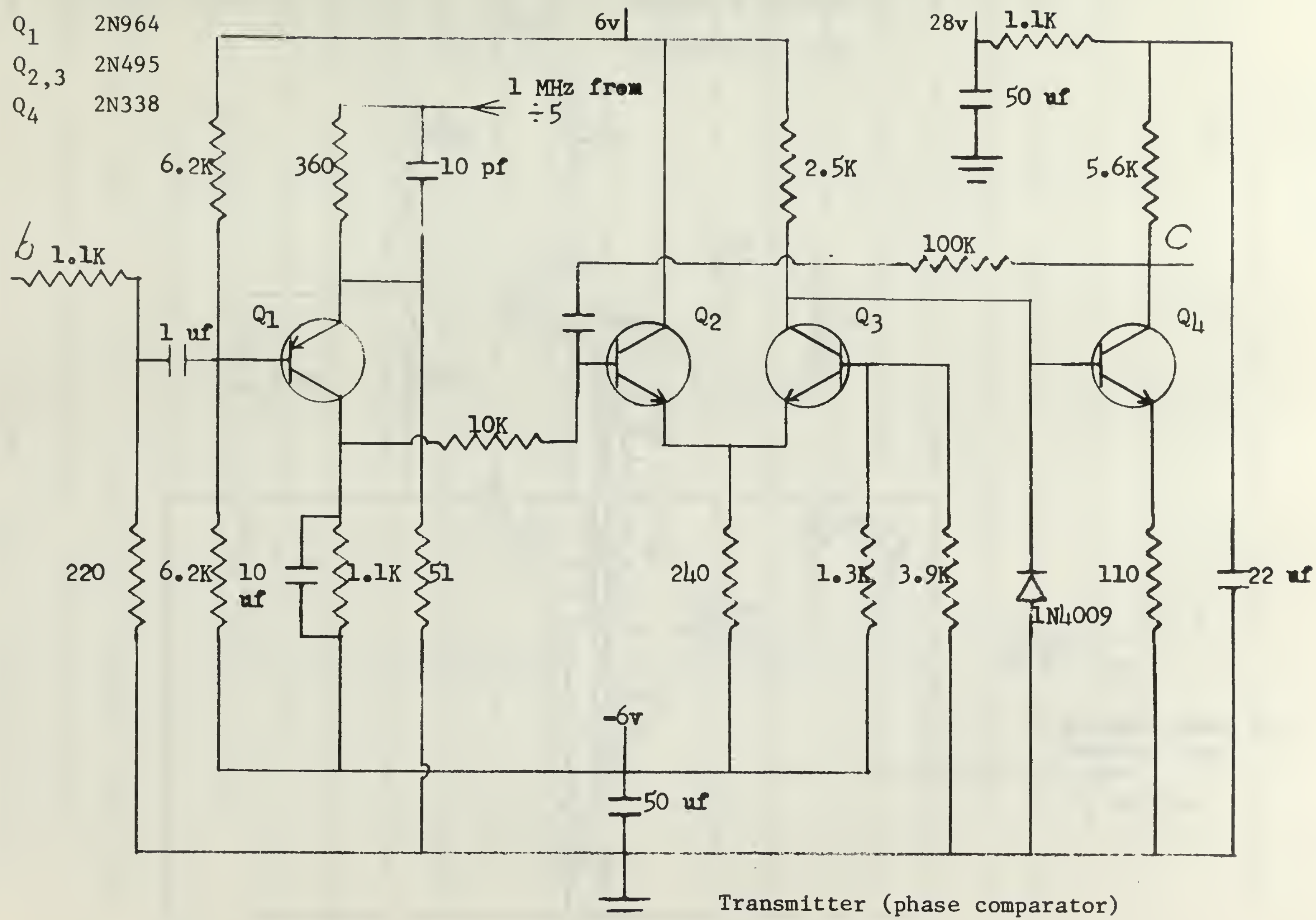
Since it was desired only to test the receiver, the transmitter was modified by removing the power amplifier, and coupling directly from the VCO into the 50 ohm receiver input, through a 10K isolation and dropping resistor. The feedback loop was then run from the output of the VCO into the divide-by-two circuit.

The following figure, 4.2, shows the VCO, the divide-by-two, and the phase comparator network. The divide-by-five is identical to that used in the receiver, and is shown in figure 5.15; the regulated power supply is also the same as that built for the receiver, less the 12v adaption, and is shown in figure 5.21. The power amplifier and transmitter stages are not shown since final modifications to them have not been completed.



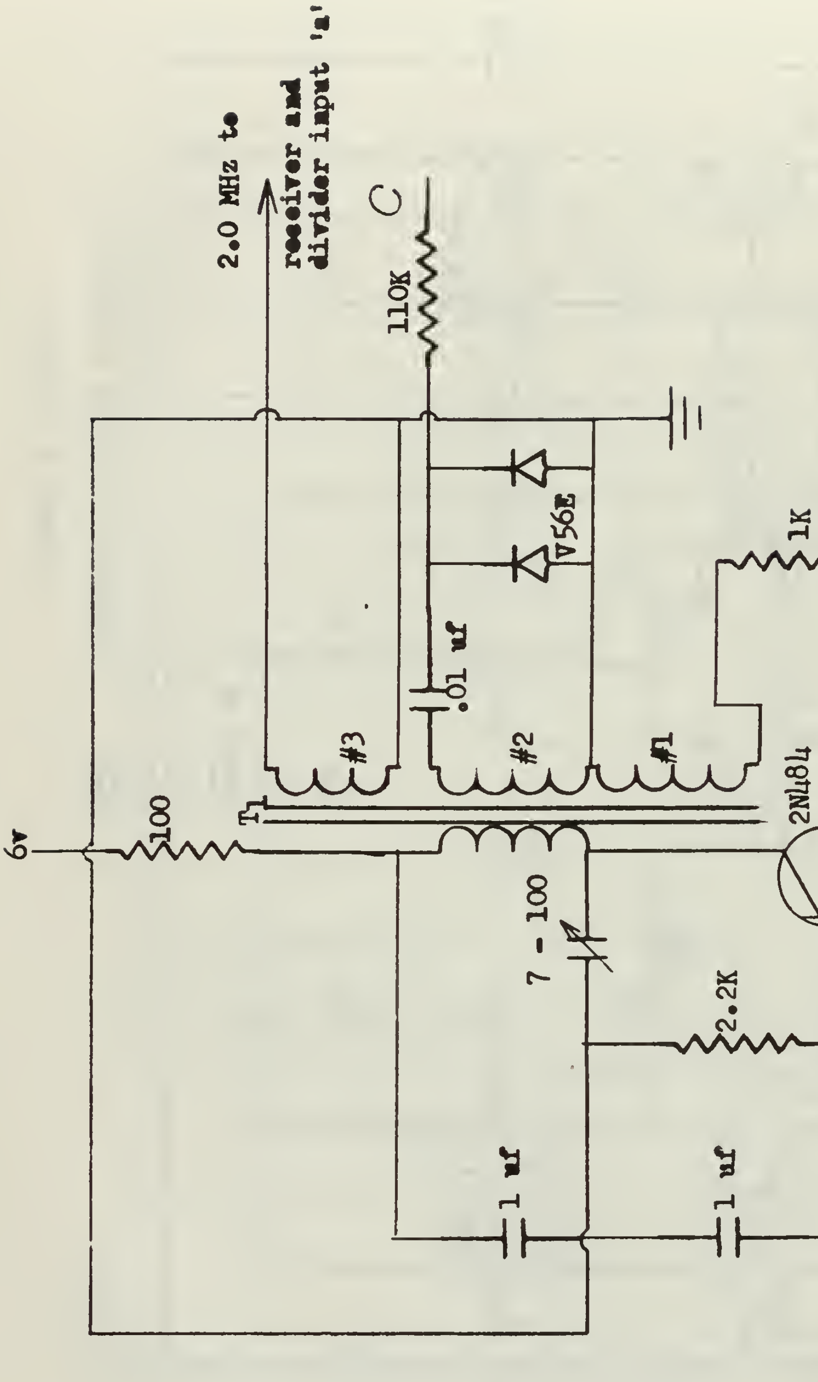
Transmitter (÷ 2)

Figure 4.2



Transmitter (phase comparator)

Figure 4.2 (cont.)



Transmitter (VCO)

Figure 4.2.(cont.)

5. The Receiver.

The design, development, and test of the receiver is the basis of this thesis, and will be studied in some detail in this section.

The three primary considerations were simplicity, economy, and especially phase stability. Earlier experience with problems of multi-harmonic frequency synthesization, oscillations, and phase instability, prompted the decision to produce as simple a system as possible. This was the main reason for the choice of a 500 KHz IF frequency, rather than the 100 KHz attempted previously. The 500 KHz reference signal is easily obtained from 5 MHz by division by 2, and then by 5. And since the transmitter operates at 2.0 MHz, the 500 MHz IF is produced by beating with the 2.5 MHz result of the division by two. Figure 5.1 shows a block diagram of the entire system.

This is a very straight forward receiver, and would be a simple design problem, except for one important requirement, which makes this system different from a normal superheterodyne -- phase stability. A standard communications receiver is primarily concerned with bandwidth and noise, while phase is unimportant. However, in this case phase stability is the all-important concern; the system is worse than useless without it. Selectivity and sensitivity are very desirable, especially from the ECM point of view, but they must be secondary to phase.

A certain phase shift through the receiver circuits is expected, and is not a problem in itself. The problem is a change in this phase with age, temperature, and physical shock. It is here that phase stability and selectivity are at odds; figure 5.2 shows the typical phase-bandwidth relationship of a linear filter. The narrower the bandwidth, the more rapid is the phase change with a change in frequency. If, because of temperature, age, or some other reason, the filter

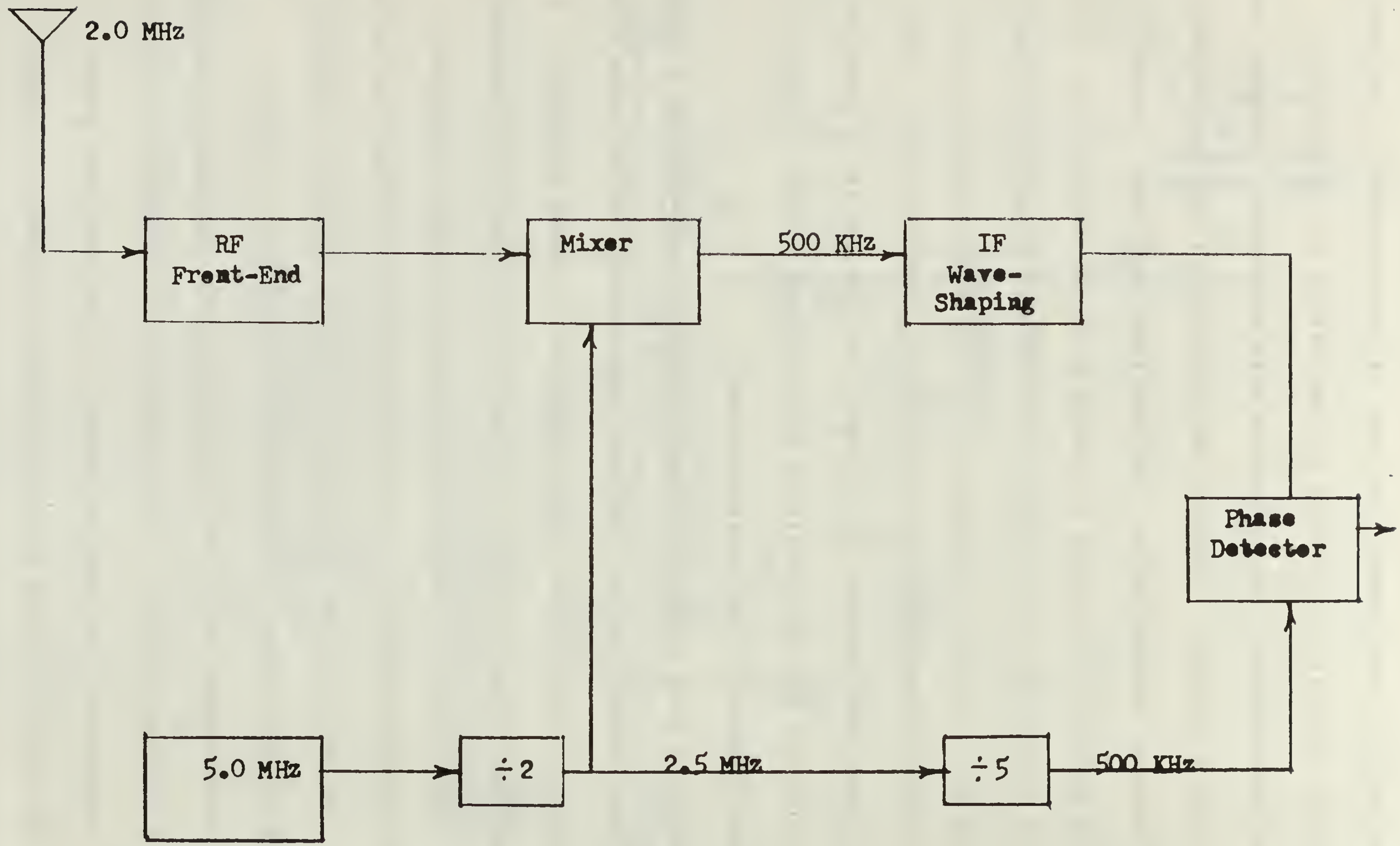


Figure 5.1. The Receiver

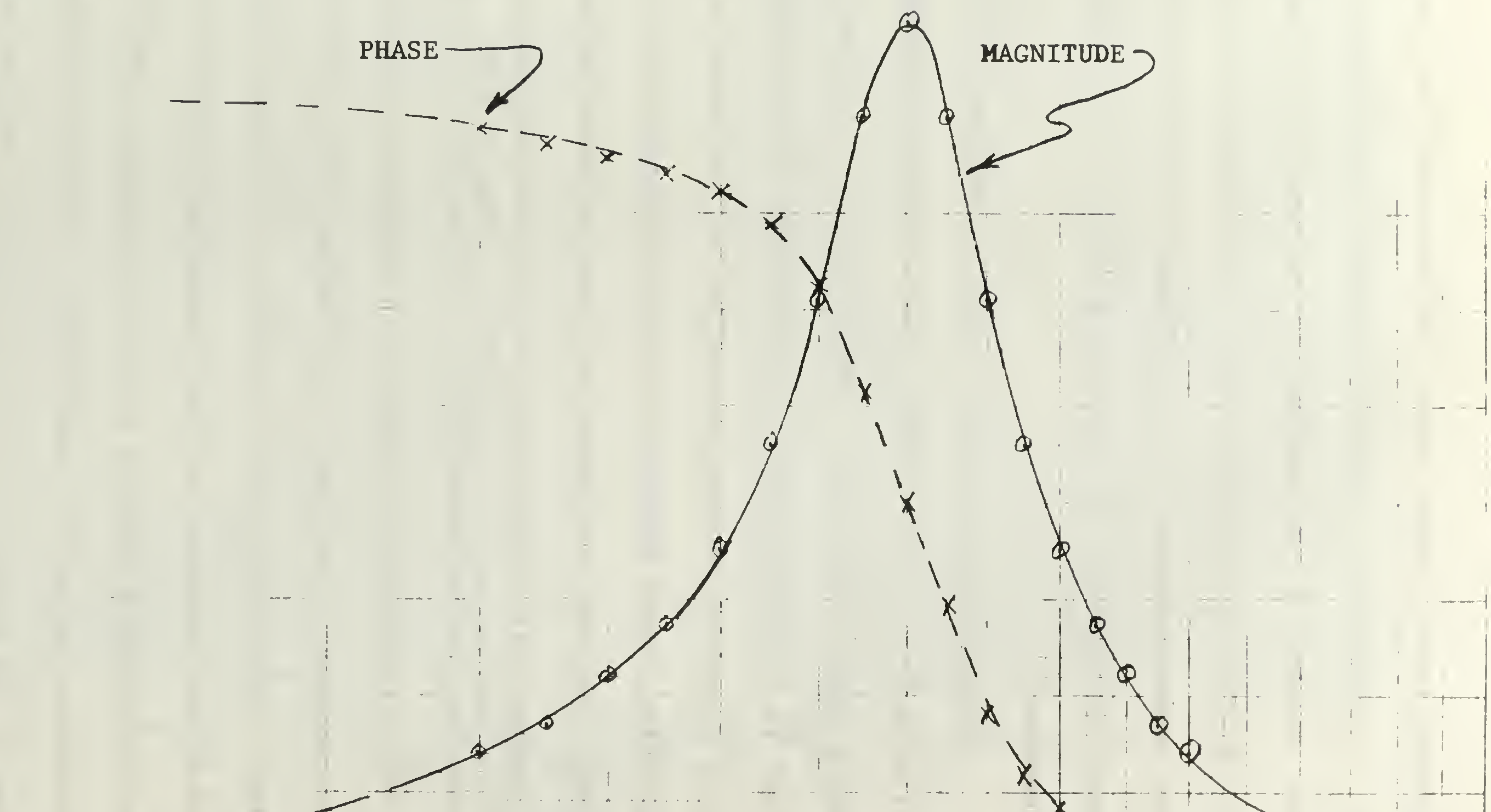
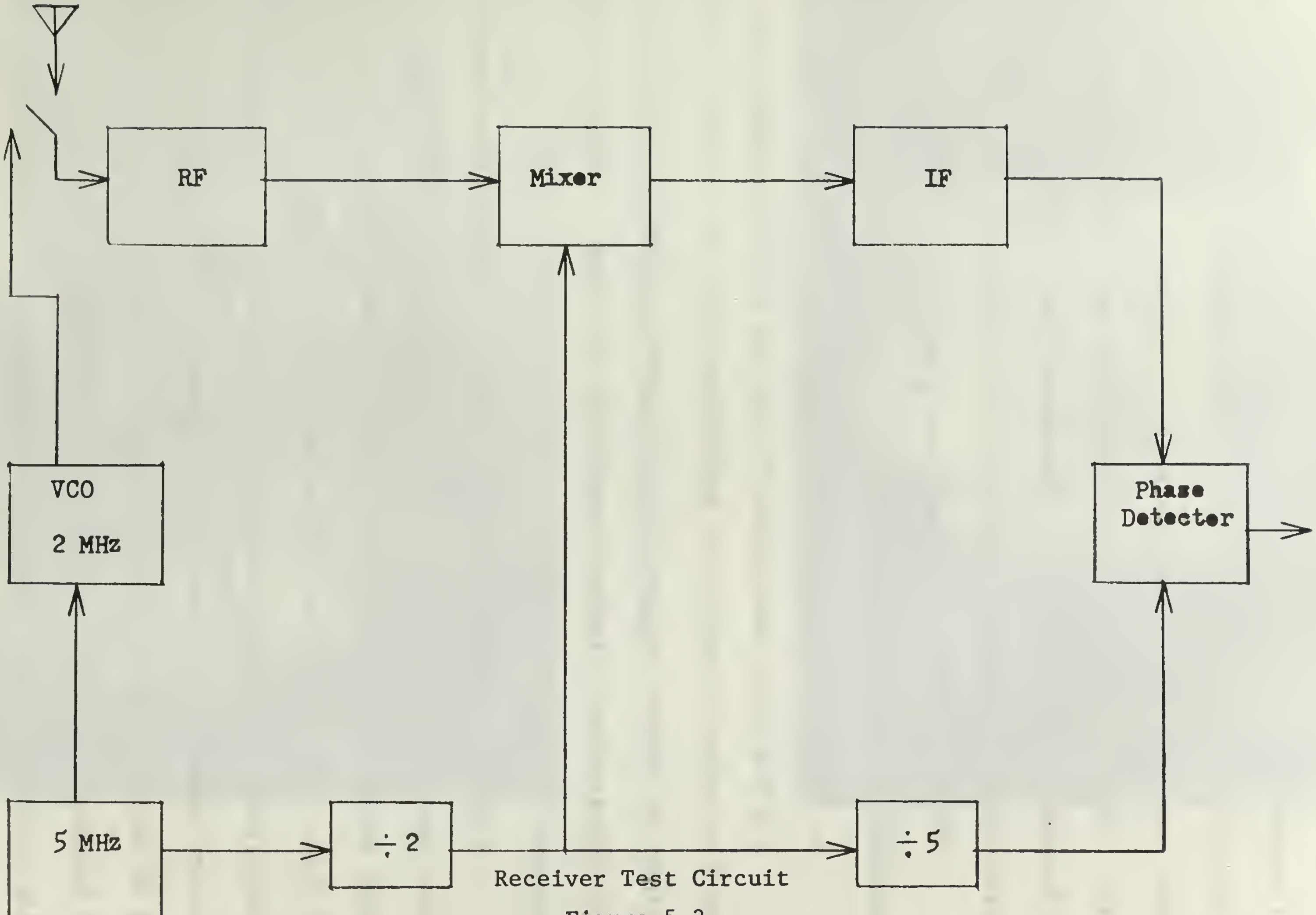


Figure 5.2

components should change value, then there will be a corresponding change in f_c. A change in f_c produces an unknown, and undesired, change in phase. Because of this problem a great deal of time and effort was spent in trying to design a narrow-band filter with a region of no phase change versus frequency. Various forms of both digital and Wiener filters were devised, but were determined to be unsatisfactory at these frequencies.

Since the problem could not be eliminated, a means of circumventing it had to be developed. The simplest method appears to be a receiver phase test circuit. This consists of a 2 MHz VCO, identical to that in the transmitter, but controlled by the local receiver oscillator. Since the critical assumption in the system is equal oscillator frequencies, there should be no phase difference due to frequency difference. The test VCO output is connected directly to the primary of the antenna coil (figure 5.3), and the resulting phase output is then due entirely to the phase shift in the receiver circuits. The receiver may then be periodically tested to determine an internal phase shift. The repetition of the tests would depend on the final stability of the system; this is dealt with more fully in the test section. These tests could either be manual, or done automatically with the result continuously subtracted from the total phase readout. The ultimate possible selectivity, and with it sensitivity, of a final receiver design will depend on the success of this test system. The present design includes only one crystal filter and a broad-tuned front-end; this was intentionally done on the prototype to reduce the number of sharp phase shifting sections. However, this made it necessary to hold the sensitivity to 25uv to reduce the effect of the strong interfering AM broadcast band (of the order of 25mv). The success of the test circuit will allow



Receiver Test Circuit

Figure 5.3

the introduction of more narrow-band filters, and hence more amplification for signal sensitivity. It must be kept in mind, however, that the test system requires that any phase changes be small over a short period of time; the cascading of many filters increases the possibility of greater changes. This, then, introduces an ultimate limit to the sensitivity. Since a primary goal of this thesis was to develop a prototype, and determine the feasibility of the overall navigation system, the determination of this limit will be left to further study.

The rest of this section will be concerned with the design considerations and analysis of the various stages of the receiver.

A. The front-end and RF amplifiers.

All the linear amplifiers of both the RF and IF stages were mounted on printed circuits and shielded in six 2.25" x 1.50" x 1.375" aluminum box chassis (figure 5.4); this prevented the oscillations to which high-frequency high-gain amplifiers are prone. Each box will be considered as a unit.

Figure 5.5 gives the circuit diagram of the front-end tuned circuit and the crystal filter. The transformer is a 3 - 60 turn toroid, which, with the two 210 - 700 pf trimmer capacitors, is tuned to 2.0 MHz. The 0.9 - 7 pf trimmer is adjusted to equal the capacitance of the crystal and holder; the intention here is that off-frequencies which are passed by the capacitive reactance of the crystal hardware, will be nullified by an equal, but opposite, signal in the other leg. This balance is achieved by the grounding of the node between the two tuning capacitors. On-frequency the magnitude of the signal passed by the crystal is such that it is practically unaffected by the nullifying leg. Unfortunately the crystal that was available for this use also passed such harmonics as 2.2 MHz, and a moderately strong 1.0 MHz signal

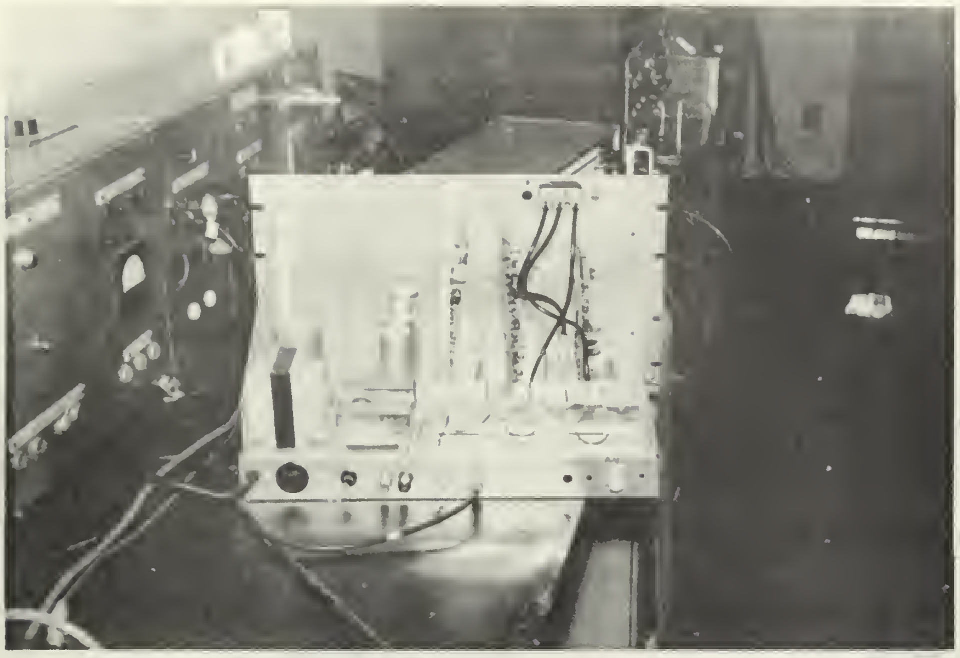


Figure 5.4(a)

Rear Views of Receiver Chassis

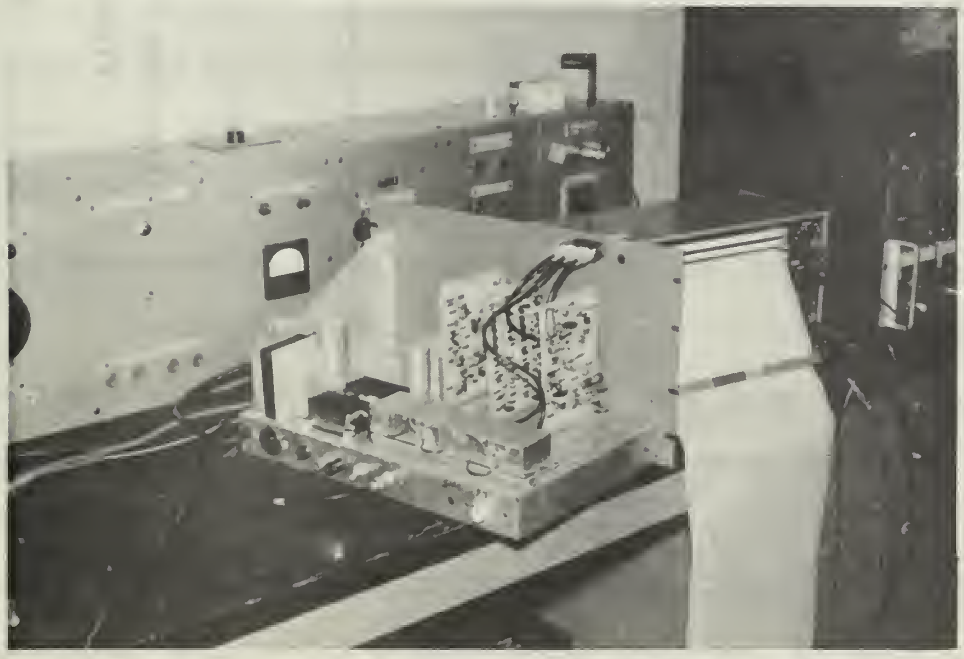
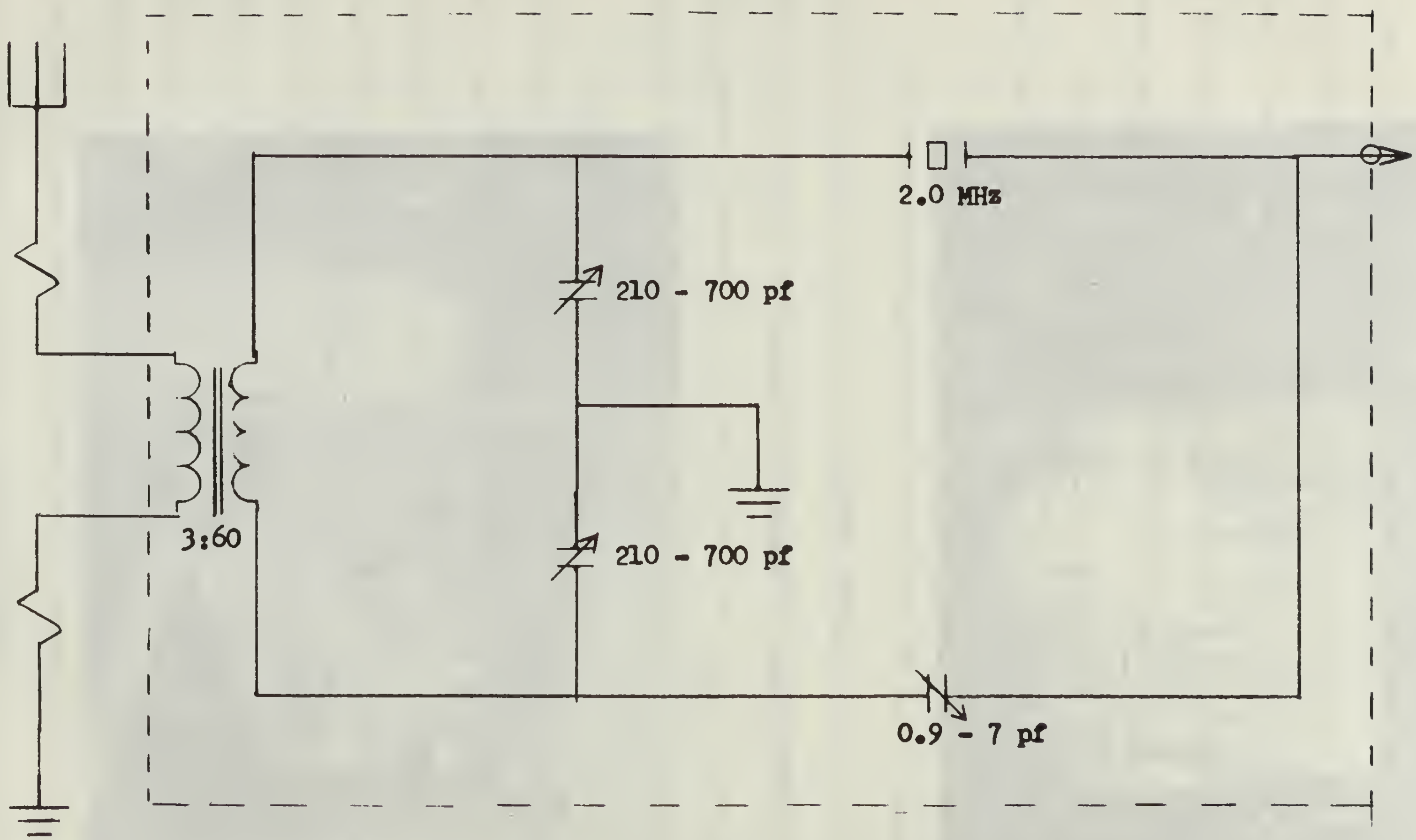


Figure 5.4(b)



Front-End Tuned Circuit

Figure 5.5

would cause the crystal to ring at 2.0 MHz. This was the main sensitivity problem, and necessitated a lower RF gain than would normally be desired. Of course the tuned toroid helped, and the filter was very sharp in the neighborhood of 2.0 MHz.

The high output impedance of the crystal caused loading problems into a normal amplifier. A standard emitter follower was also unsatisfactory. It was therefore determined to use a Darlington type, bootstrap, emitter follower. The resulting design is shown in figure 5.6. Millman and Halkias[(4)] give the approximate input impedance of this circuit, less biasing and load, as $R_i \simeq h_{fe1} h_{fe2} R_e$;

$$R_e = 10K \parallel 12K = 5.46K$$

$$h_{fe1} \simeq 400$$

$$h_{fe2} \simeq 100$$

$$\therefore R_i \simeq 220M.$$

The input impedance, therefore, depends almost entirely on the biasing circuit, and almost total isolation is achieved. The biasing impedance consists of 200K in series with the parallel combination of 390K and 1M; 480K. It was found that the circuit was more satisfactory in this configuration than with the first transistor also boot-strapped.

The following stage -- figure 5.7 -- is a high gain RF amplifier, with a total ac voltage gain of 29 db. This is followed by a medium gain amplifier -- figure 5.8 -- designed to drive the 50 ohm input of the RELCOM mixer. It has an ac voltage gain of 21 db. Each stage of RF has a B+ line filter consisting of a series 240 ohm resistor followed by a 10 uf capacitor to ground. It is effective, and will not be mentioned further; it is not shown in the schematics.

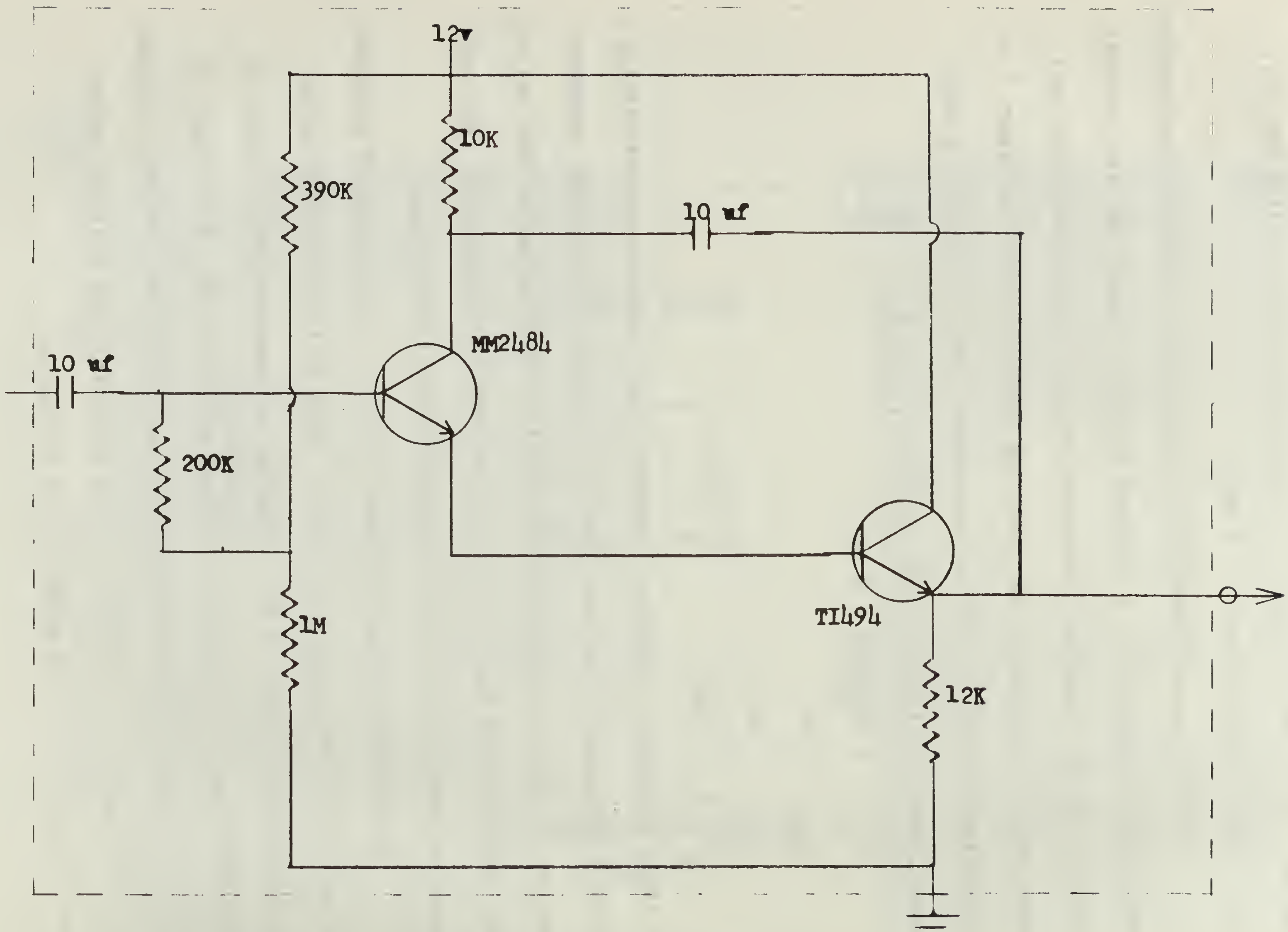


Figure 5.6. Darlington Emitter Follower

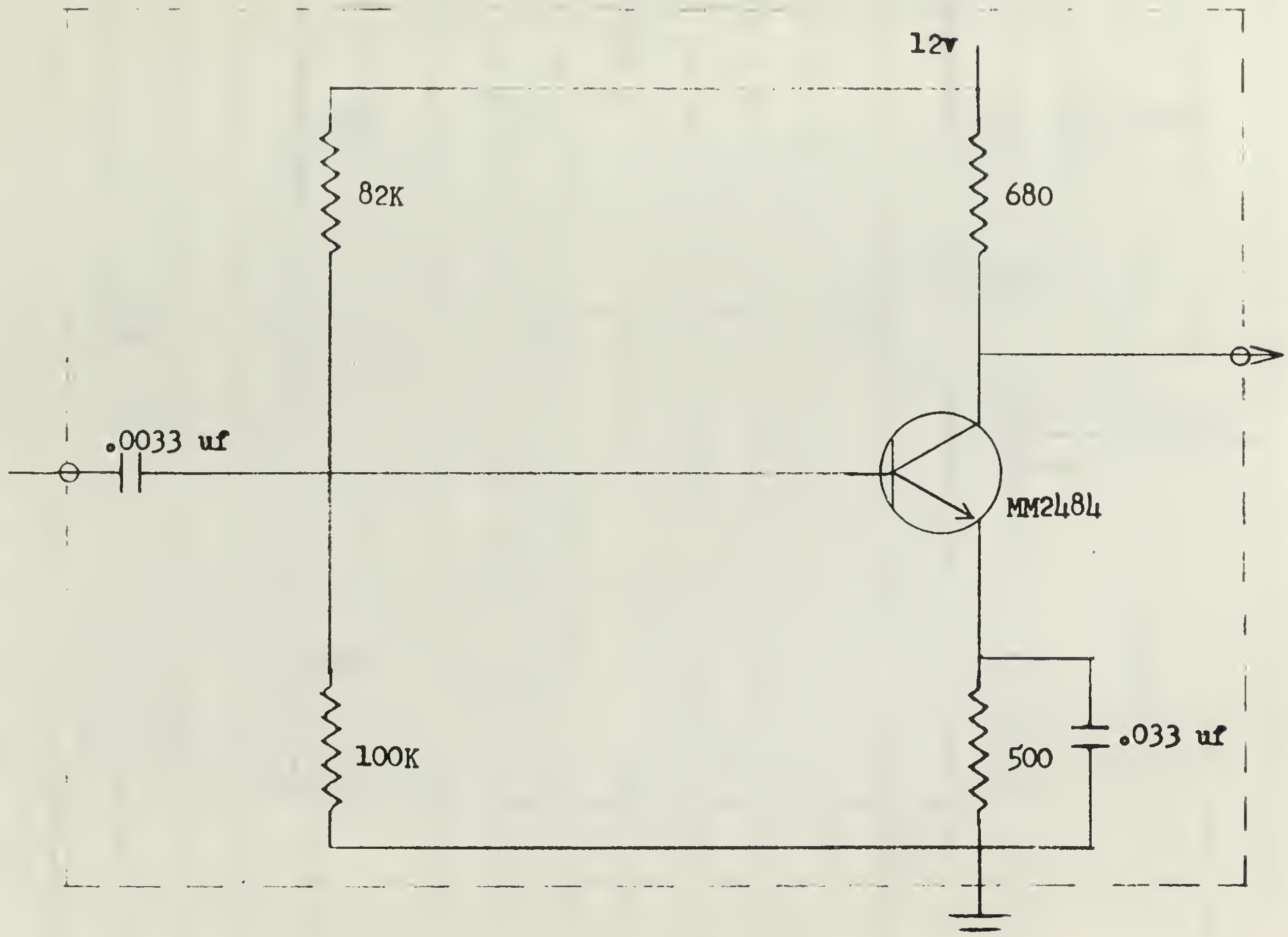


Figure 5.7. High Gain RF Amplifier

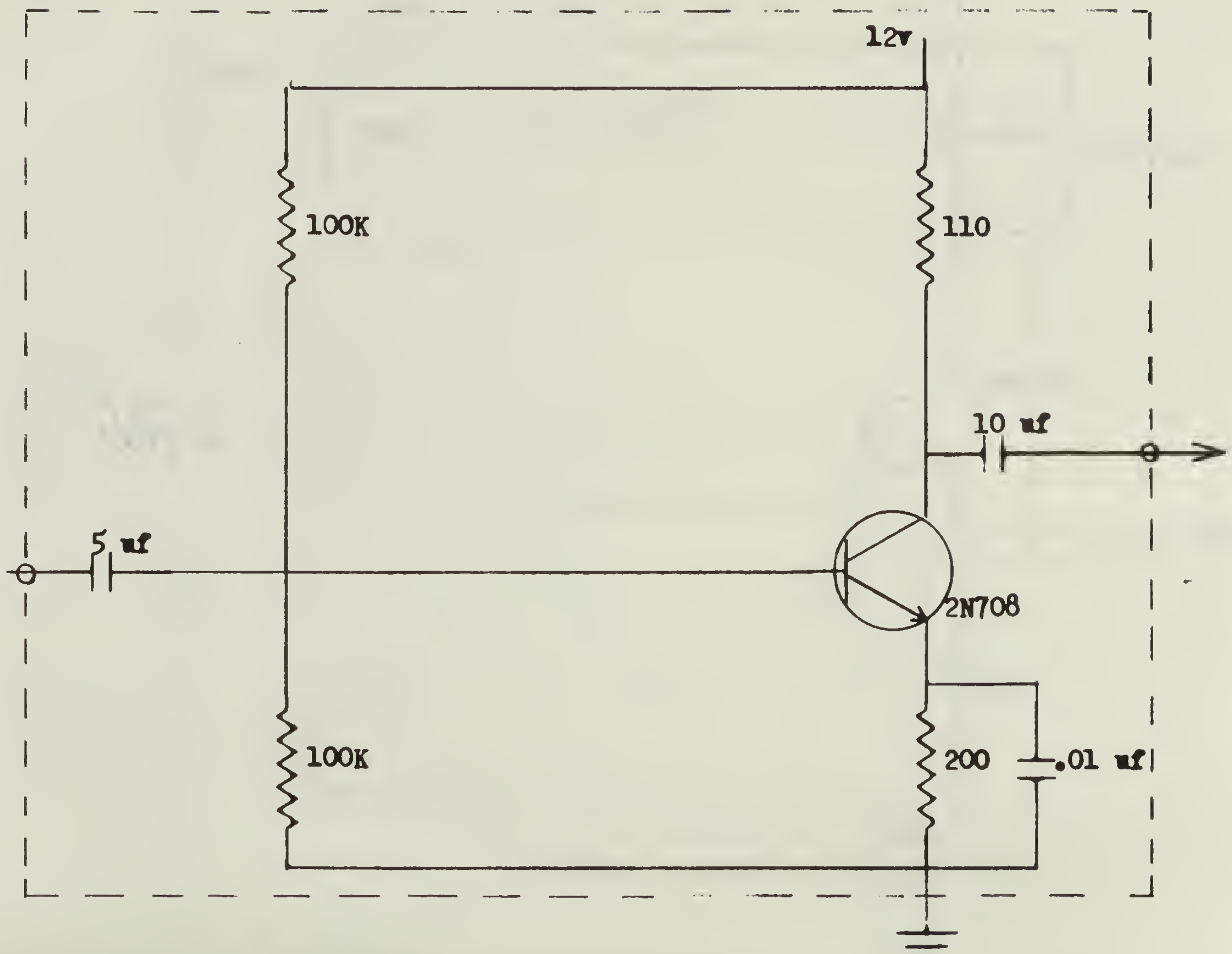


Figure 5.8. Medium Gain RF Amplifier

B. The mixer.

The RELCOM mixer[5] is an excellent device with a very low noise figure. It also has a high degree of isolation between ports, and extremely good suppression of all but the sum and difference frequencies. It equaled or surpassed the mixer specifications in all respects. Figure 5.9 shows the two input signals at 2.0 MHz and 2.5 MHz, and the resulting output fed into a low pass input impedance.

C. The IF stages.

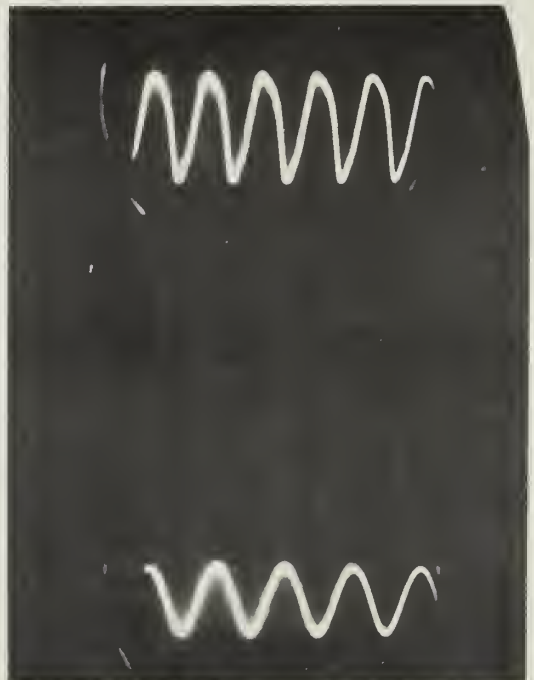
There were similar considerations in the decision to use the RCA 3002 Integrated Circuit[6] in the first stage of IF amplification. It is a medium gain (24 db) broad-band amplifier with good temperature stability and limiting characteristics. The external circuitry is shown in figure 5.10. The 100 ohm - .003 uf RC filter has a 3 db point at 530 KHz, and attenuates the sum frequency of 4.5 MHz by a factor of 11.5. The 200 ohm B+ resistor is necessary to drop the 12v supply to the 10v limit of the amplifier. Figure 5.11 gives a typical output signal.

The following transistor stage further amplifies and limits the signal for improved noise suppression; the output -- figure 5.12 -- is limited for all but the smallest RF input signal.

A high impedance Schmitt Trigger was necessary at the following stage to prevent loading of the limiting amplifier, and to provide a definite input to the phase detector. Figure 5.13 shows the circuit that was developed, while figure 5.14 gives the sharp 500 KHz output signal. It was found that the Zener diodes in the base and emitter legs of the first transistor provide an extremely high input impedance, until breakdown voltage is reached, and a very stable trigger level for the circuit; a 5v input is required for trigger.

2.5 MHz
Figure 5.9(a)

2.0 MHz
Figure 5.9(b)



500 KHz
Figure 5.9(c)

Inputs

Output

Mixer Wave-Shapes

Figure 5.9

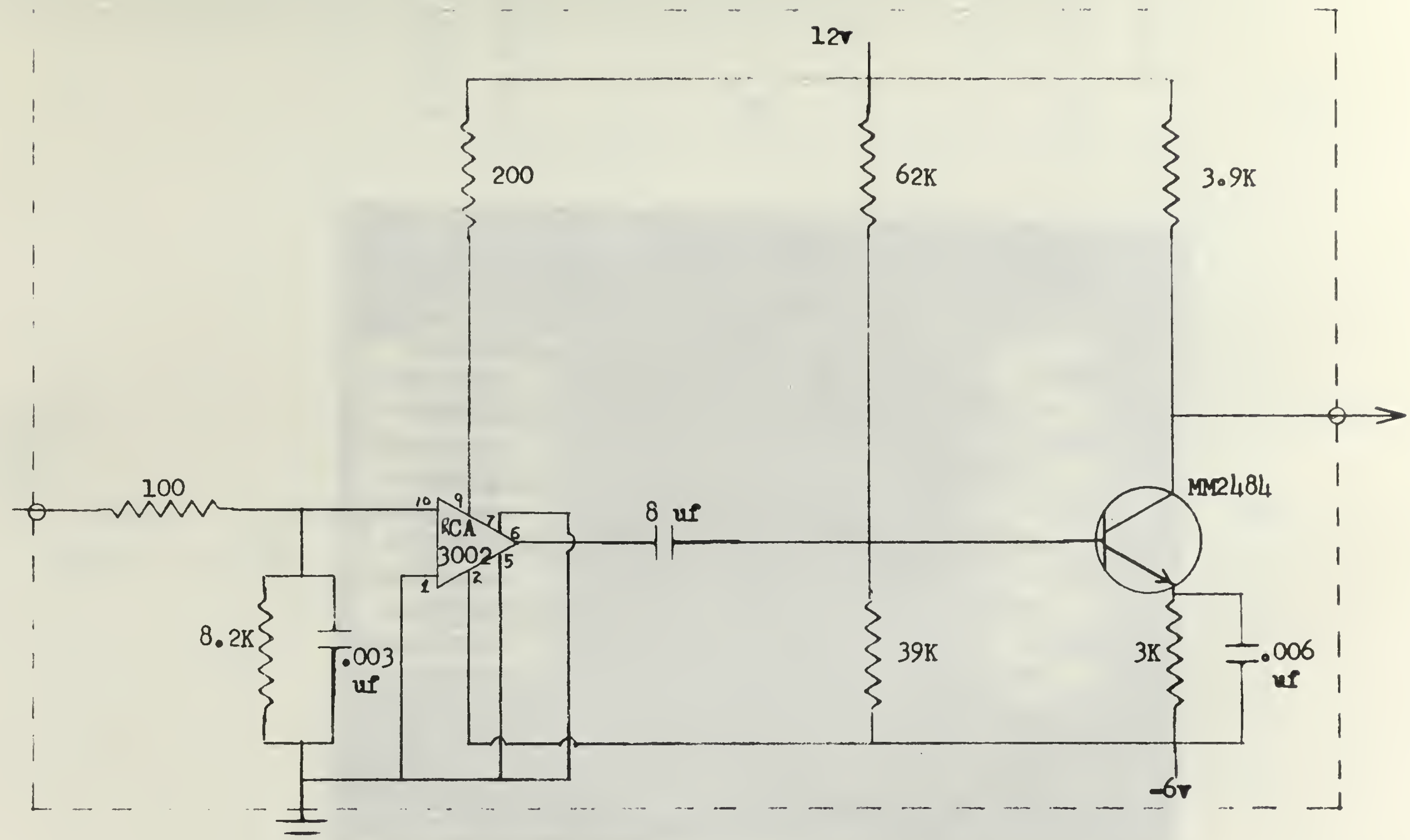
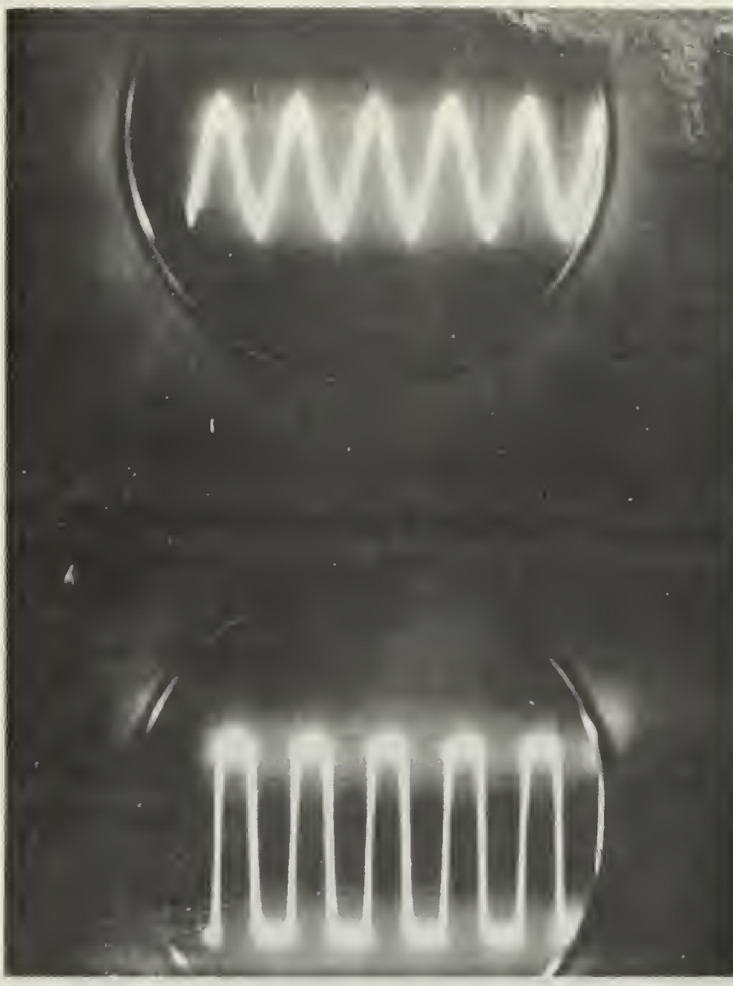


Figure 5.10. IF Amplifier and Limiter



IC Output

Figure 5.11

Limiter Output

Figure 5.12

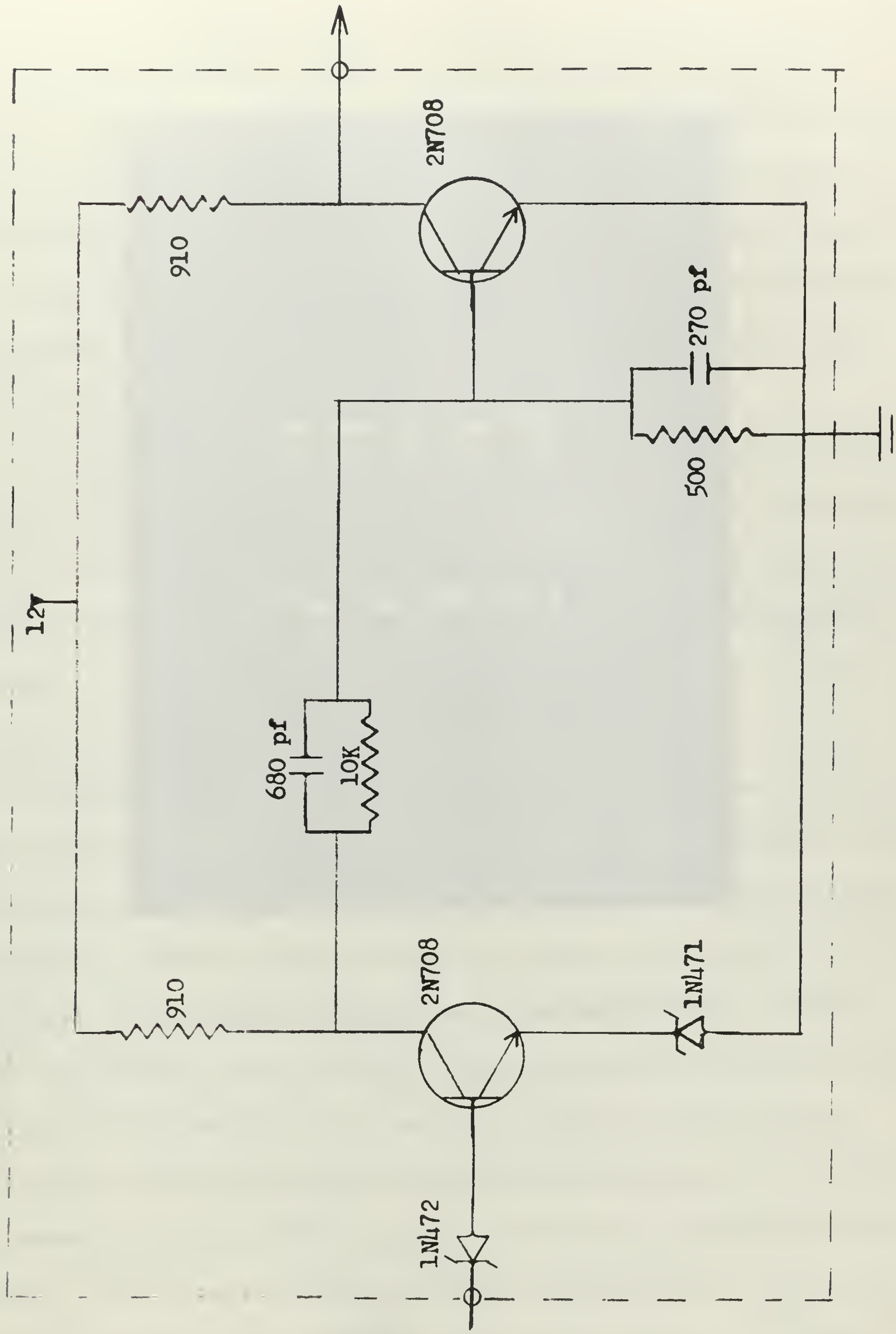
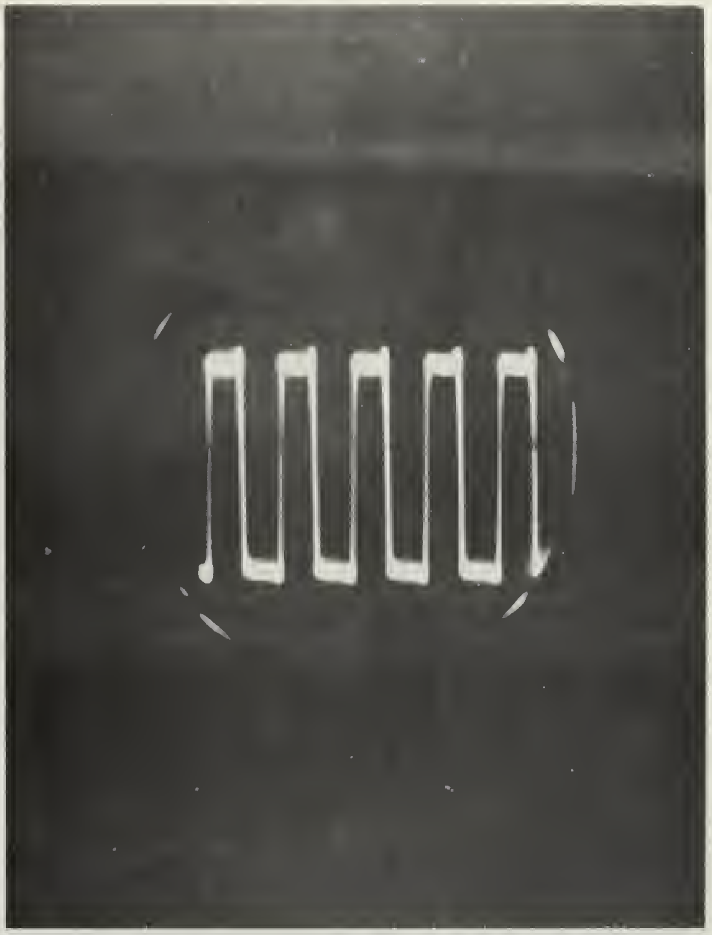


Figure 5.13. 500 KHz Schmitt Trigger



500 KHz Schmitt Trigger Output

Figure 5.14

D. The divider circuits.

The divide-by-five circuit used in the transmitter, the test system, and the receiver are almost identical to those designed and built for Dean's thesis. Figure 5.15 gives the schematic, while figure 5.16 shows the block diagram of the circuit. It is a standard binary counter with a feedback loop to produce the double shift necessary for division by a non-power of two. The divider is followed by a monostable flip-flop to even out the output square wave.

The divide-by-two circuit -- figure 5.17 -- is a simple bistable flip-flop, whose response is intentionally slow with respect to the 5 MHz input. This produces an output which more closely resembles a sine wave; the desired form for the mixer input. Figure 5.9(a) is a photograph of this signal.

E. The phase detector.

The phase detector circuit -- figure 5.18 -- is drawn in block diagram form in figure 5.19. Its operation is relatively simple. The positive-going signal at input one sets the binary counter with a high level output; a similar signal at input two resets the counter to a low level output. This is done at the mutual frequency of the two inputs; in this case 500 KHz. The dc level of this unsymmetrical 500 KHz square wave is directly dependent on the degree of symmetry, which in turn depends on the time lapse between the set and reset signals -- a function of the phase difference. Obtaining this dc level is a simple RC filter operation. This circuit was designed with a potentiometer to allow for some degree of output level control; it was set to allow for a seven volt swing -- -1.5v - +5.5v -- which is required to control the varicaps in the Sulzer oscillators. This permits the initial frequency locking referred to in the oscillator section.

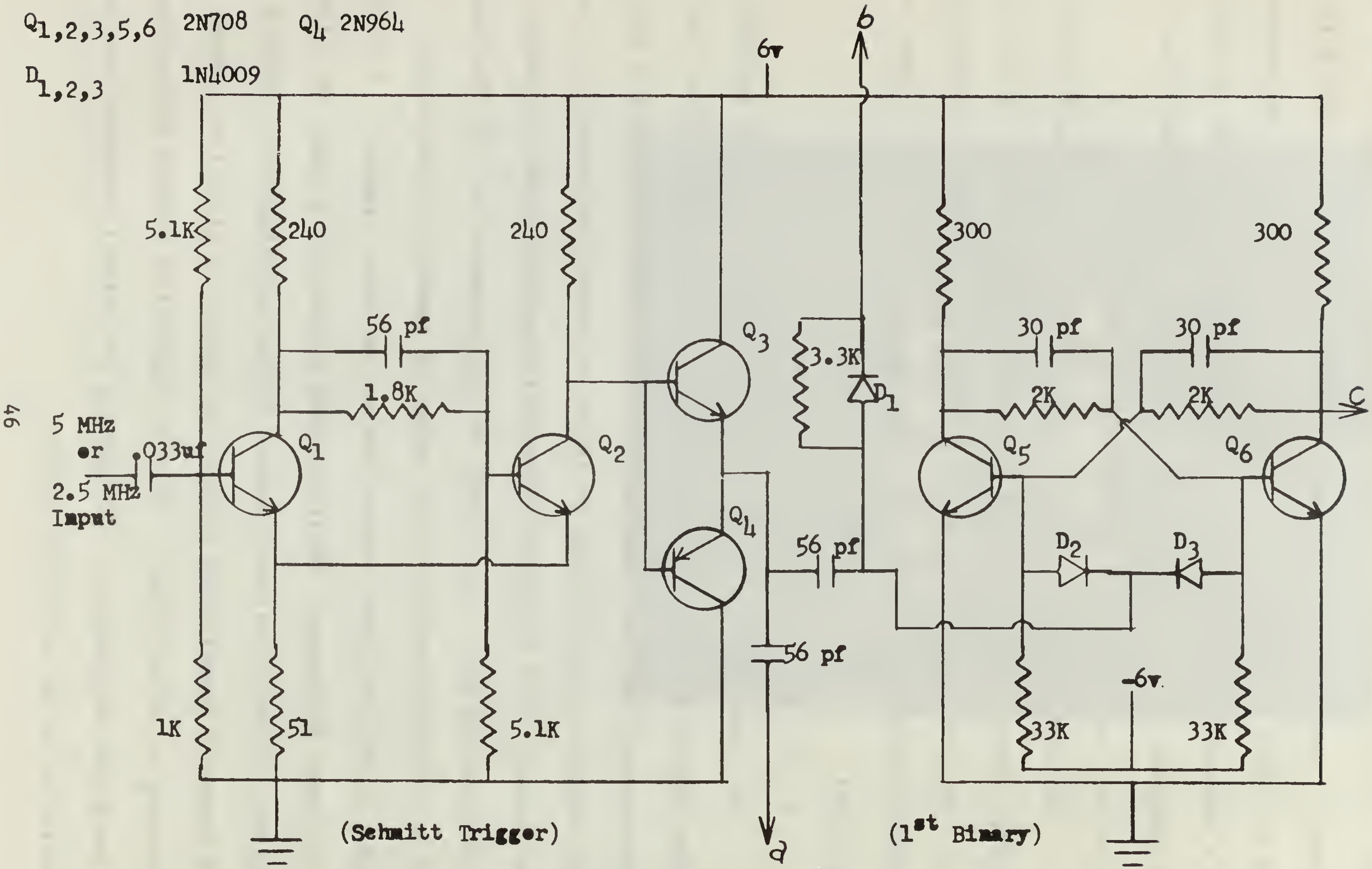


Figure 5.15. Divide-By-Five

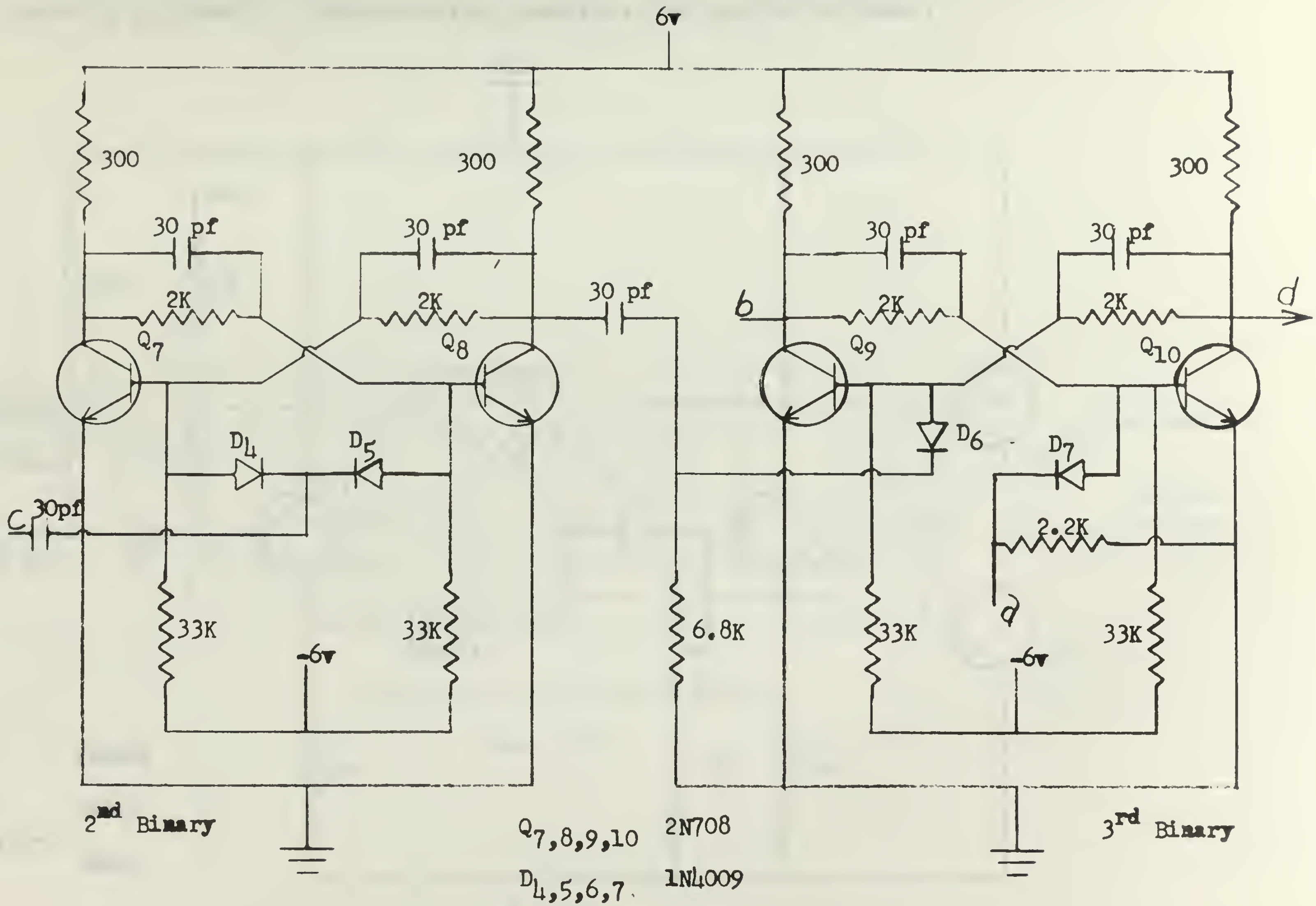


Figure 5.15 (cont.). Divide-By-Five (Binaries)

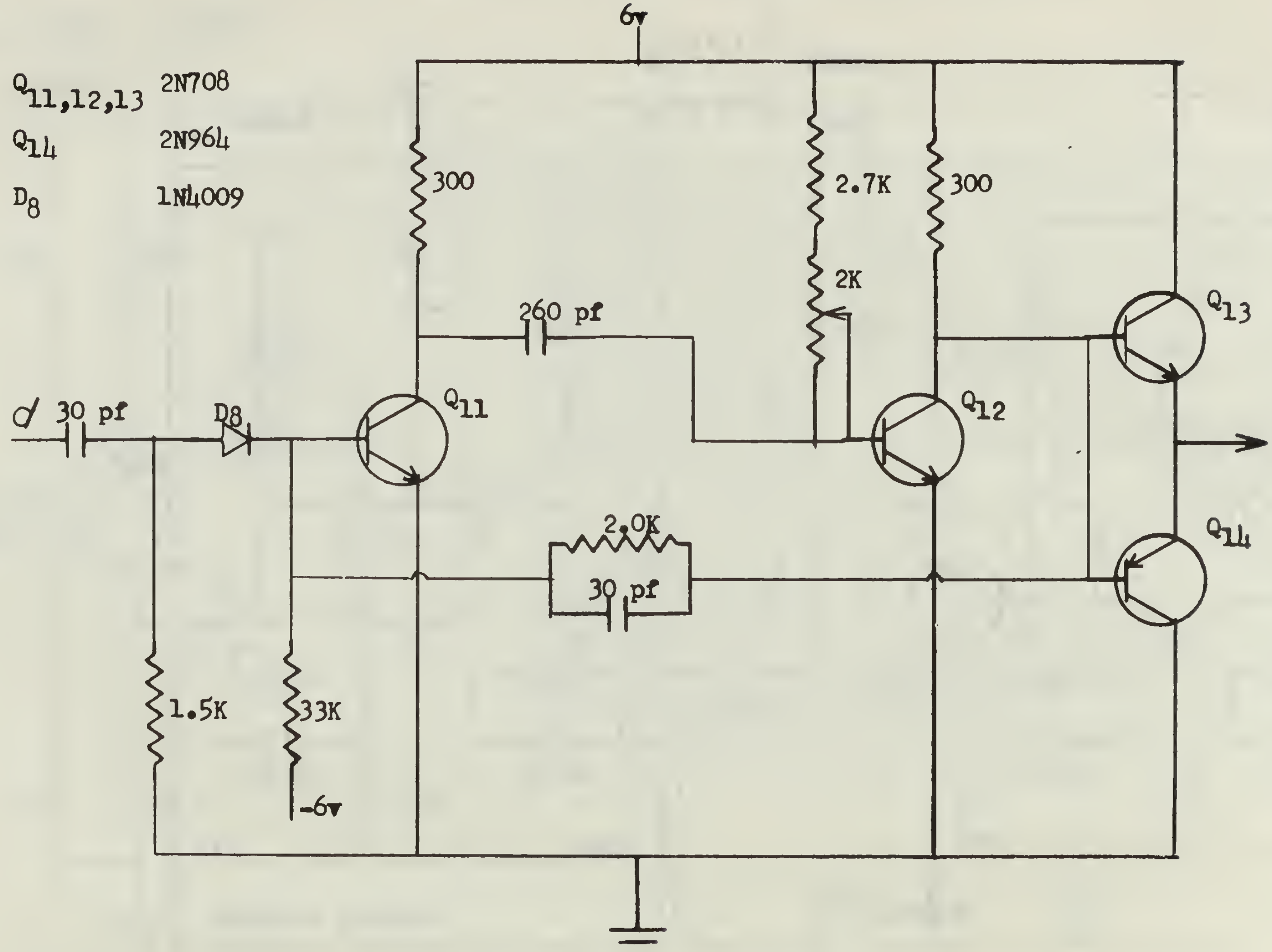
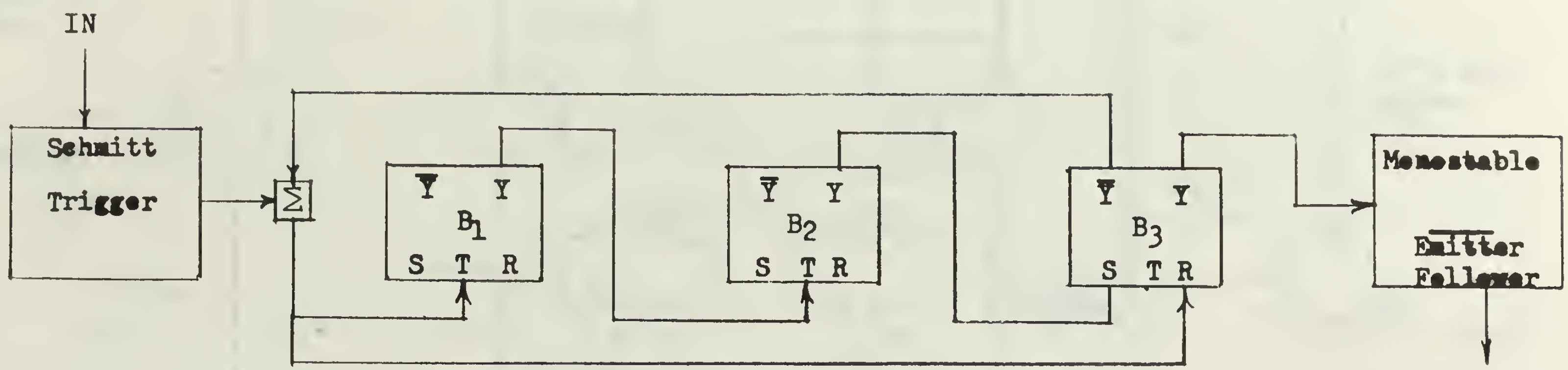


Figure 5.15 (cont.). Divide-By-Five (Monostable and Emitter Follower)



Divide-By-Five (Block Diagram)

Figure 5.16

$Q_{1,2,3}$	2N708
Q_4	2N336
$D_{1,2}$	1N4009

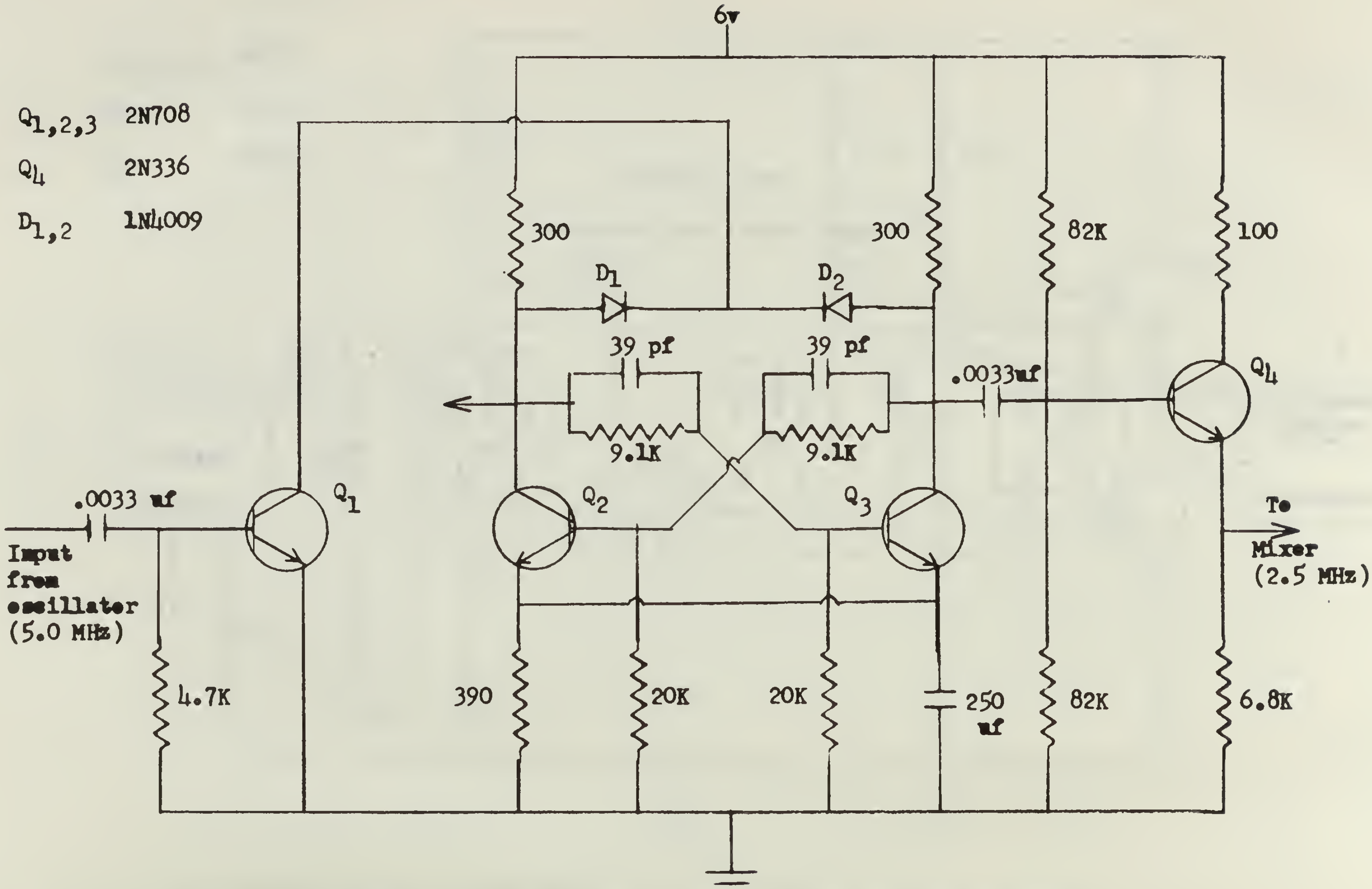
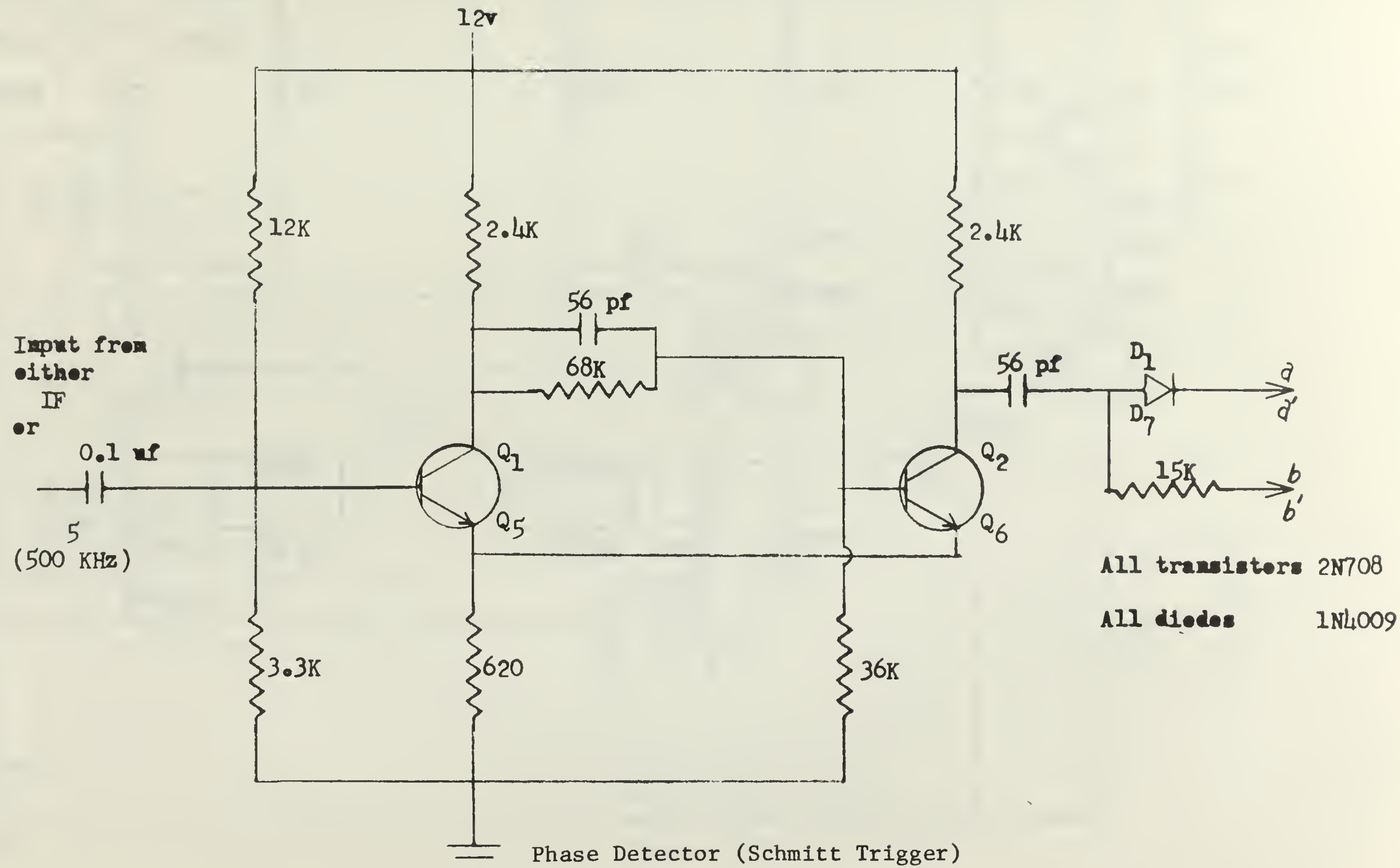


Figure 5.17. Divide-By-Two



Phase Detector (Schmitt Trigger)

Figure 5.18

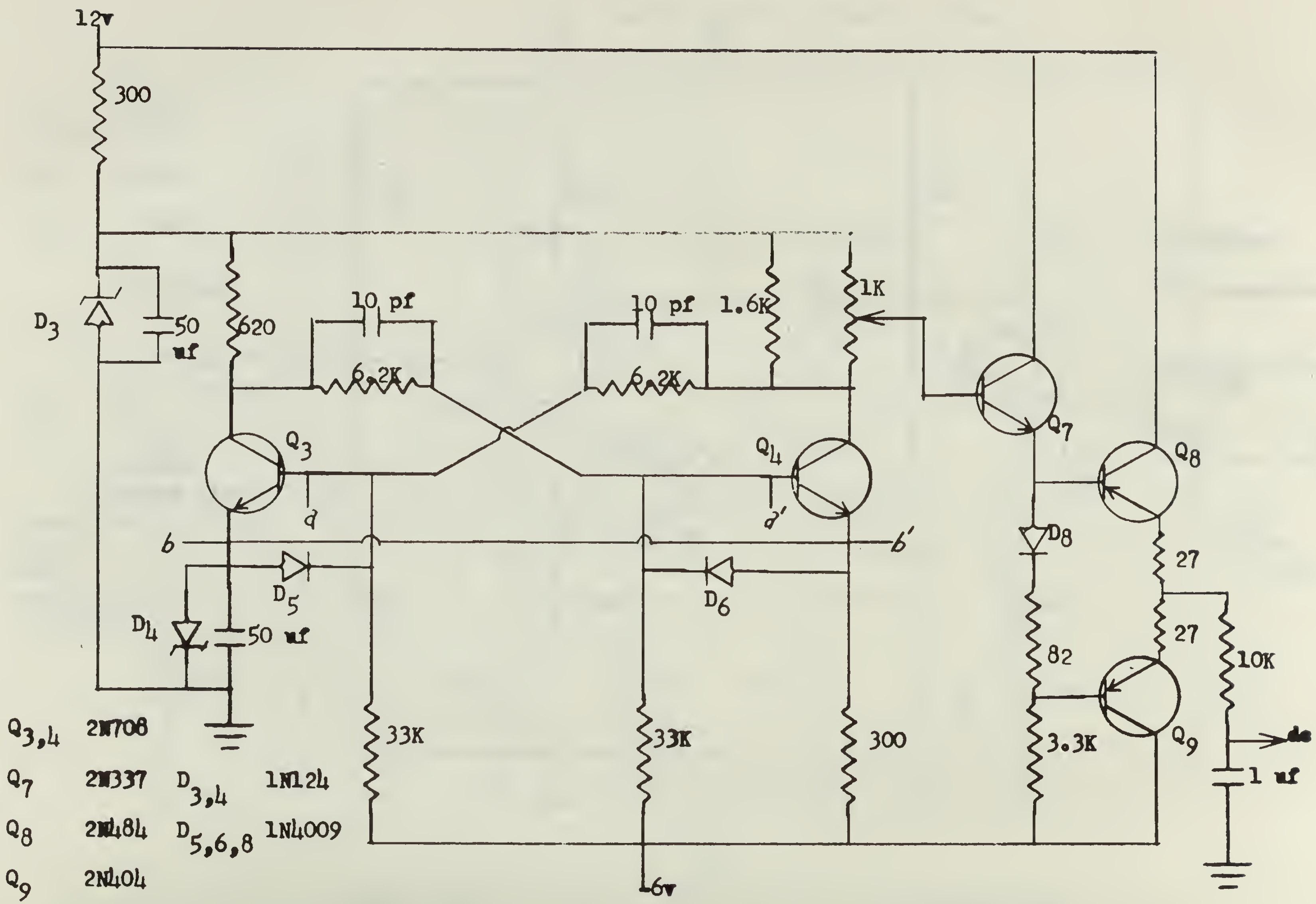
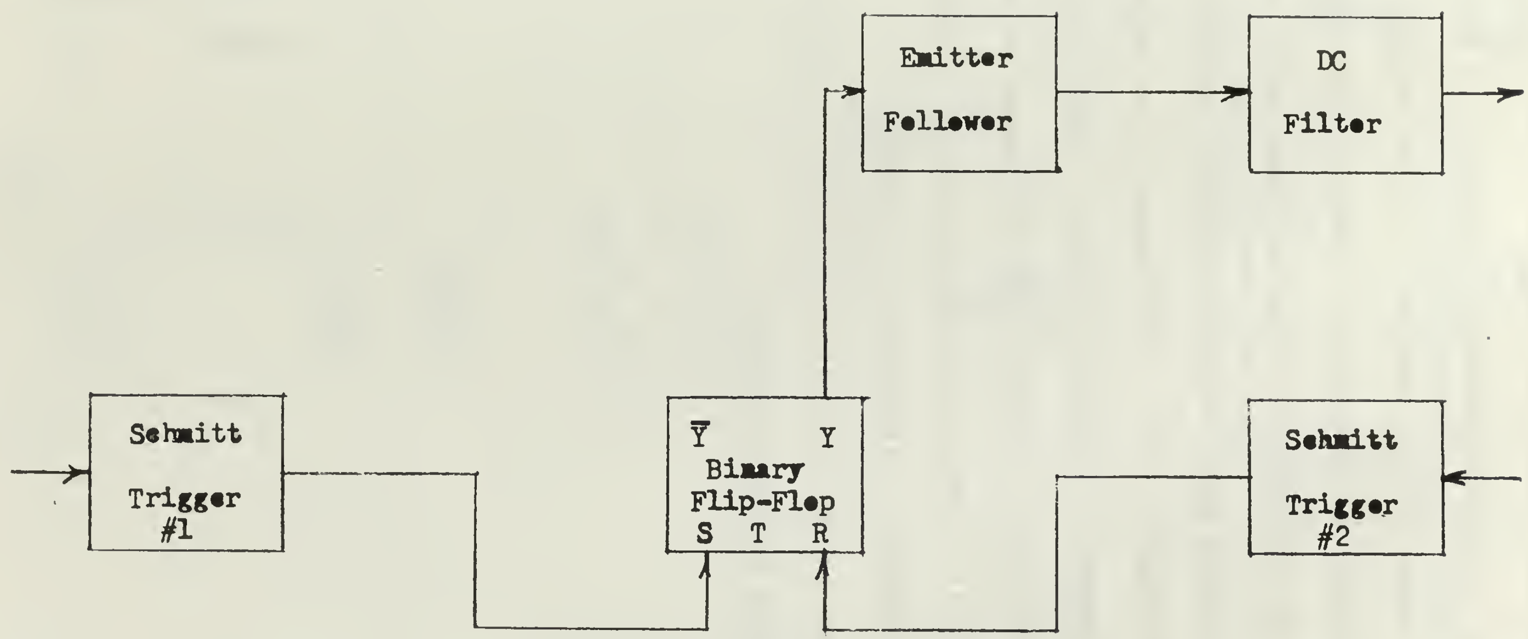


Figure 5.18 (cont.). Phase Detector (Bistable and DC Filter)



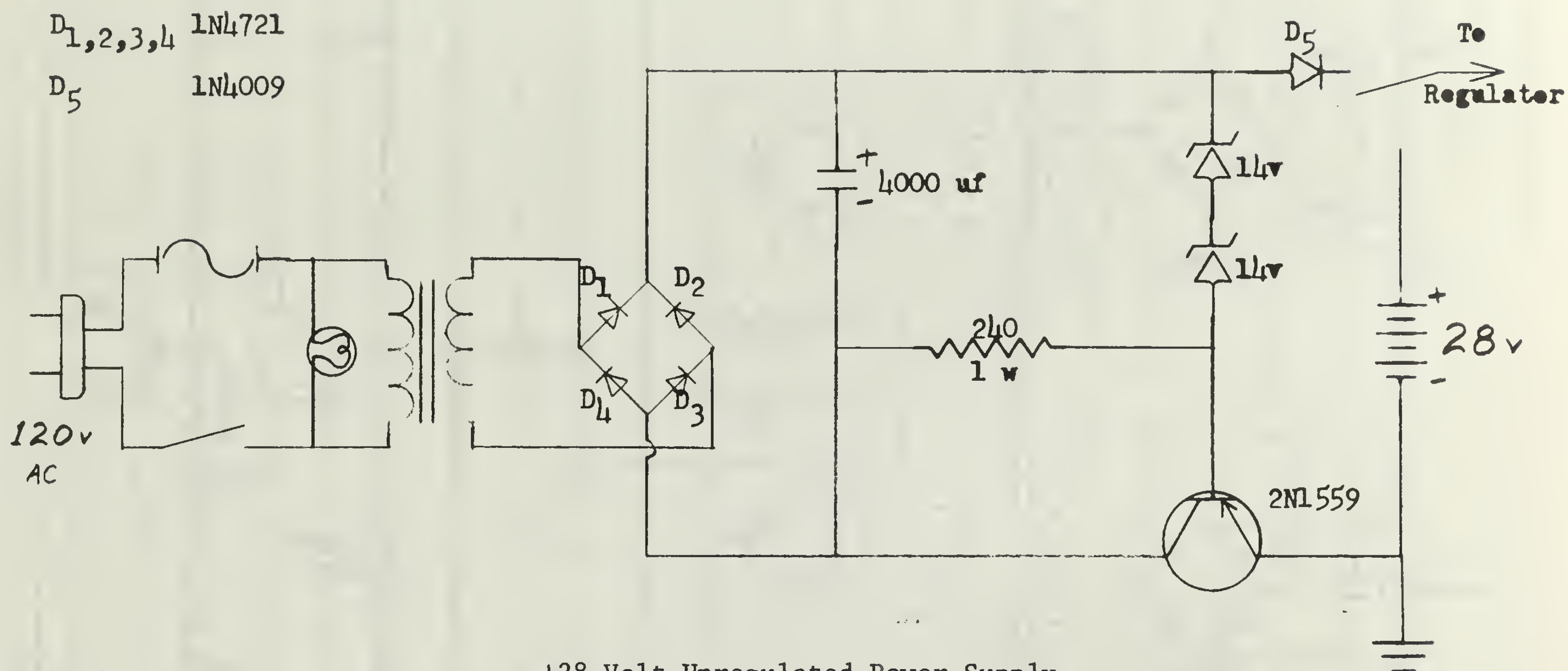
Phase Detector (Block Diagram)

Figure 5.19

F. The power supply.

The power supply was designed in two sections; the first in figure 5.20 is an unregulated 28v rectified ac to dc supply, while the second -- figure 5.21 -- consists of a 22v voltage regulator feeding a dc - dc chopper converter unit. There are then +22v, +12v, +6v, and -6v available for the receiver circuits. This split arrangement allows for a possible switch to a 28v battery supply, and still run the local oscillators on a regulated 22v. Unfortunately the chopper converter produces a certain amount of undesirable noise. Unless the receiver is expected to be solely battery operated, this system is not recommended for future work. While it is not unsatisfactory, it is a source of unnecessary noise, and should be eliminated, if possible.

Tests on the stability, et cetera, of the receiver will be covered in the following section.



+28 Volt Unregulated Power Supply

Figure 5.20

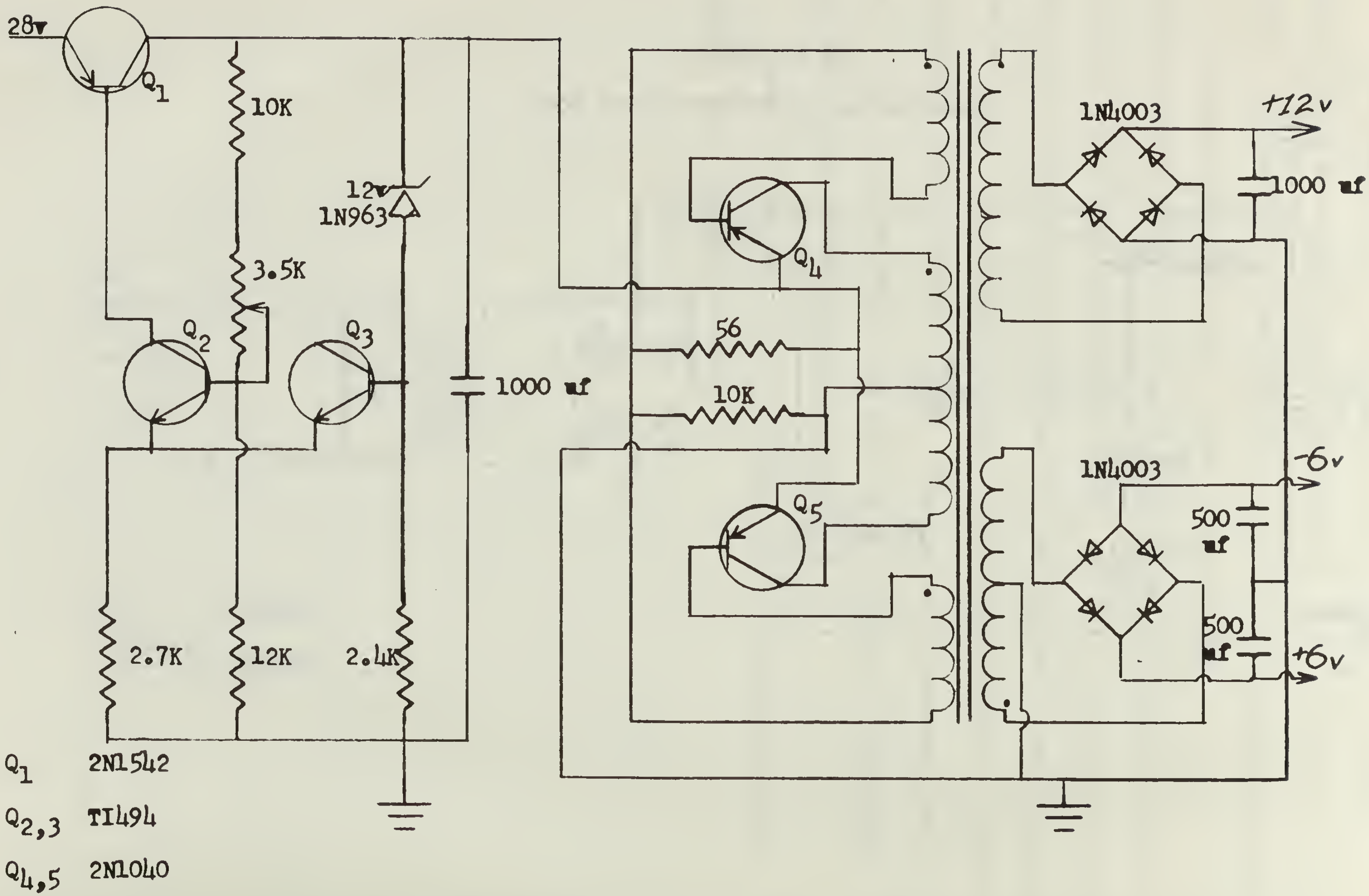


Figure 5.21. Regulated Power Supply

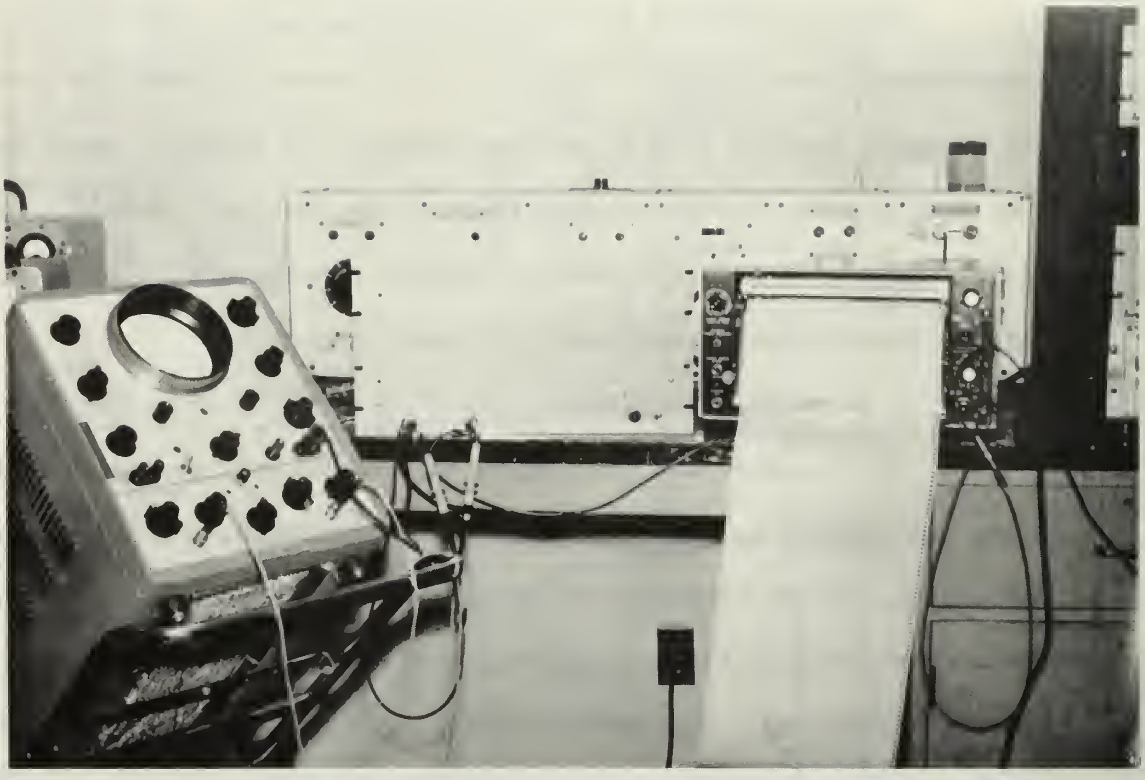
6. Receiver Tests and Results.

A. Self-stability.

The receiver was run in the receiver test position, figure 5.3, continuously for 48 hours. It was also repeatedly subjected to shock by dropping one end from an average height of 3 inches. There was no noticeable phase change recorded during this period. This test was run in a well ventilated room with an ambient temperature of 28°C, and very little temperature change over a 24 hour period.

B. Temperature effects.

The receiver was once again run in the test position, and a heat lamp was focused on the rear of the unit. The VCO, which is temperature sensitive, as was mentioned in section 4, was not subjected to the heat. This does not effect the usefulness of the test system since the sensitivity appears as a loss of frequency lock; this frequency lock is easily reobtained, and there is no resulting change in the phase lock of the VCO. A test run consisted of heating the receiver up to 43°C, and then allowing it to cool again to room temperature. Figure 6.2 shows the results of one of these runs. The vertical axis is phase change in degrees, relative to normal at 28°C, while the horizontal axis is temperature change in degrees Centigrade relative to 29°C; the o's represent data taken with the heat applied, while the x's represent data taken in the cooling off period. The middle curve is the average of the two. Note that the curve is not linear, and that there is a wide discrepancy between the system changes occurring during heating up and cooling off. Also note that although this curve is representative of $d\emptyset/dT$, it could not be used for an accurate calibration. What is important about this test is that, while the system is temperature sensitive,



Front View of Receiver

and Test Equipment

Figure 6.1

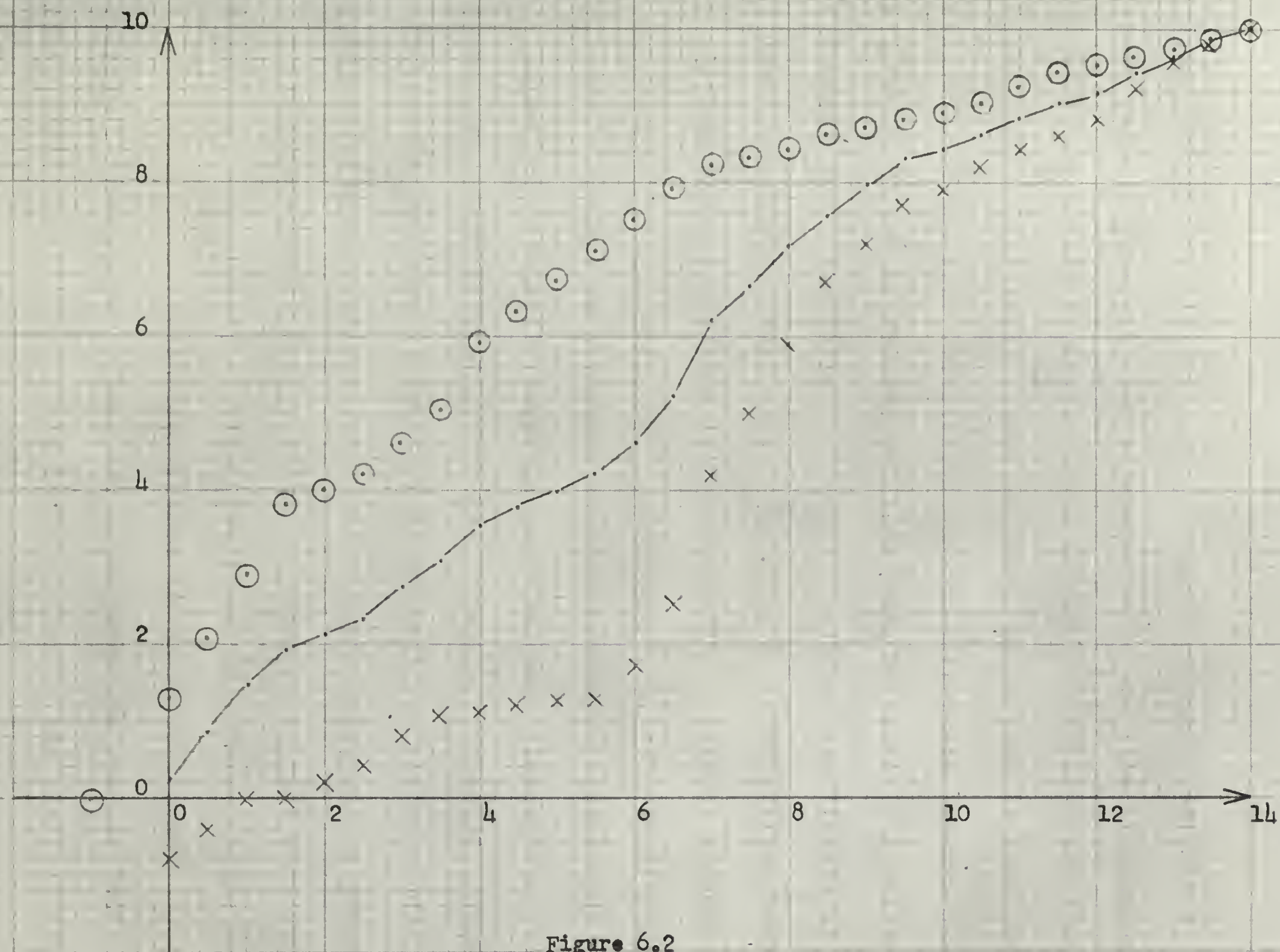


Figure 6.2

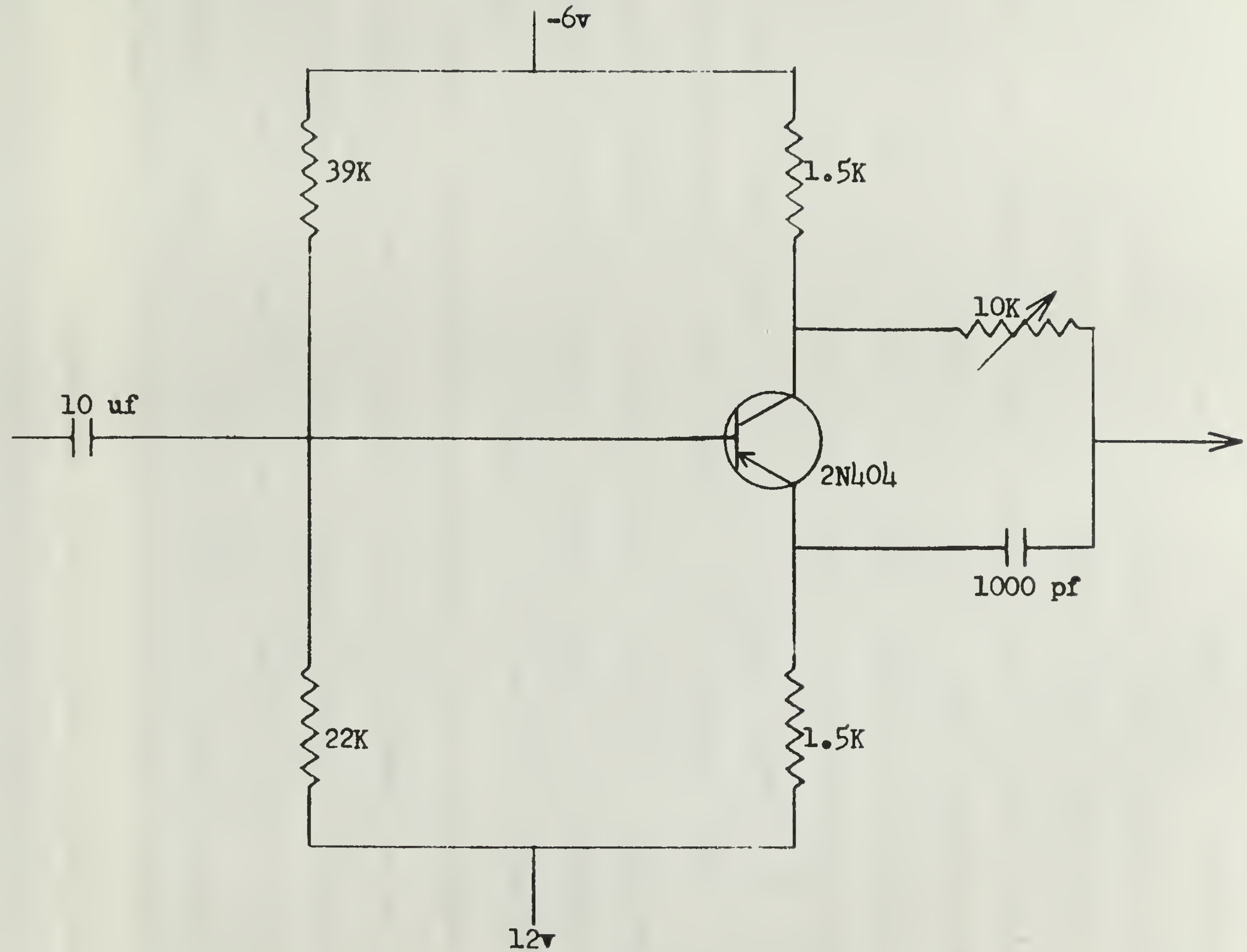
and it was expected to be, the temperature dependence is not extremely great. A 14°C temperature change is greater than would normally be encountered by the receiver. Two conclusions may be reached from these results.

Since the change in receiver phase is small over normal temperature changes it will not be necessary to make frequent receiver tests. Unless extreme temperature changes are expected, a test check of no more than once an hour would certainly appear sufficient. Also, since the phase changes are small, but not negligible, they can be corrected by inserting a variable RC phase shifting network in the RF stages. A simple RC circuit was inserted to test the validity of this suggestion, and proved satisfactory. Figure 6.3[7] is a proven design, although it would probably require a certain amount of modification for proper matching with the rest of the units.

This second recommendation was commented on earlier. The receiver is certainly acceptable as is, especially for short range situations. However it was mentioned in the introduction that improvement of the receiver would depend on the test circuit and the overall sensitivity to temperature and shock. The results of both of the above tests indicate than an increase in amplifier and filter stages for improved signal selectivity and sensitivity is feasible and recommended.

C. Phase locking of the master oscillators.

The receiver was operated in the configuration shown in figure 3.2, with feedback and without external bias, for 24 hours. Once again there was no noticeable evidence of any phase change at the output of the receiver. In this test, oscillator #2 (of 3 available) was the master, and oscillator #3 was the slave. It remained in perfect phase



RC Phase Shifting Circuit

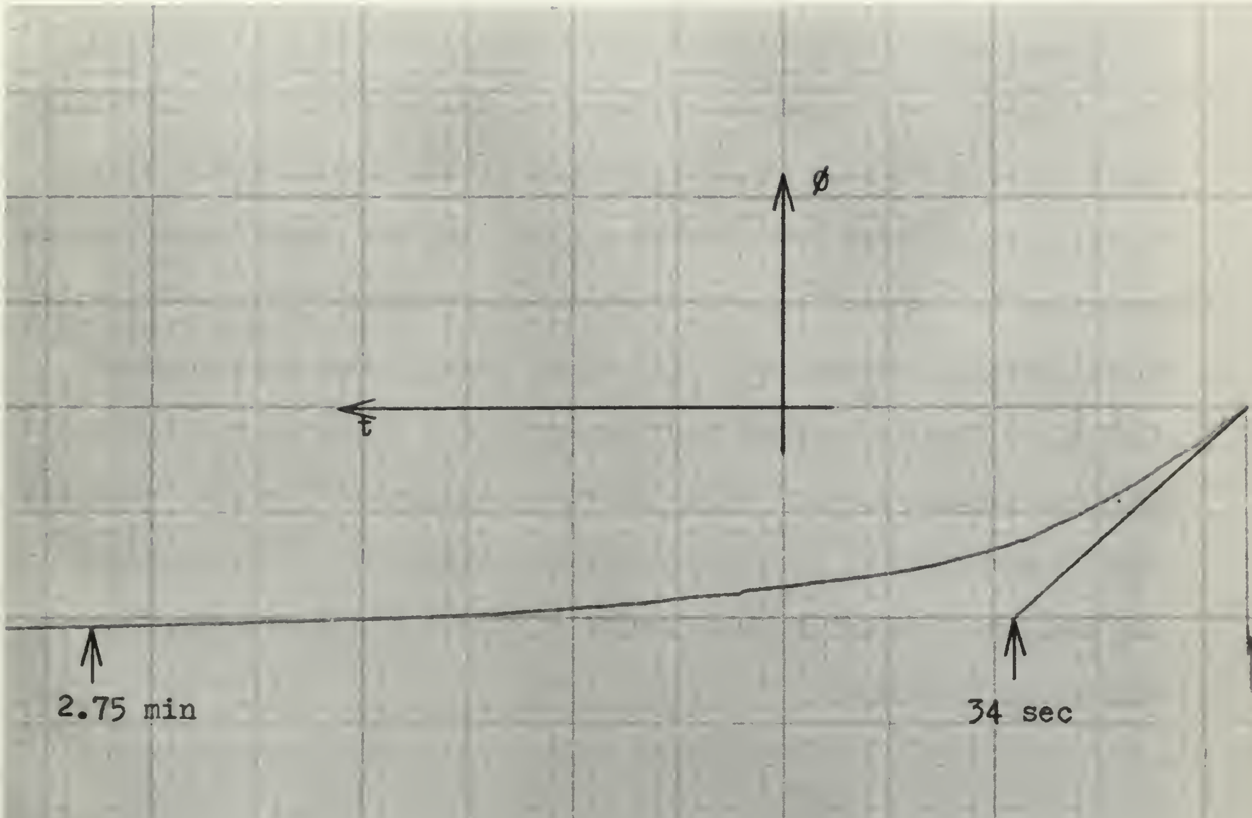
Figure 6.3

lock. An important consideration in this test was time to 'lock on.' It took, on an average, approximately one minute to manually adjust the slave into the electrically controllable region. Once this was achieved the feedback system time constant became dominant. Several tests were run to determine this; figure 6.4 gives an example of the step response. The time constant was determined to be 32.55 ± 2.25 sec. Using the standard of five time constants for decay, the recovery time is equal to approximately 2.7 minutes. Allowing another minute to adjust the varicap holding voltage, a total time of five minutes will be necessary to adjust the receiver oscillator upon commencement of the run.

D. Complete system test under two independent oscillators.

It is this test which will determine the overall feasibility of the system. The set-up was as described in the transmitter section; the transmitter VCO, under the control of one oscillator, was fed into the RF input of the receiver, under the control of another oscillator. The output of the phase detector was plotted on a strip recorder. A test run consisted of electrically aligning the receiver oscillator, as in the above test, and adjusting the holding voltage; removing the 'locking' circuit feedback, and running the system independently for 10-12 hours. Tests were run with both the #1 oscillator and then the #2 oscillator acting as the transmitter control, while the receiver was always under the control of the #3 oscillator.

The receiver operated satisfactorily in all respects. However the oscillator drift rates were still the limiting factor. But they depend to a certain extent on the accuracy and stability of the holding voltage. Even the present system of nulling a microammeter proved to be extremely sensitive, and it was difficult to achieve an equal



Scale: 2"/min.

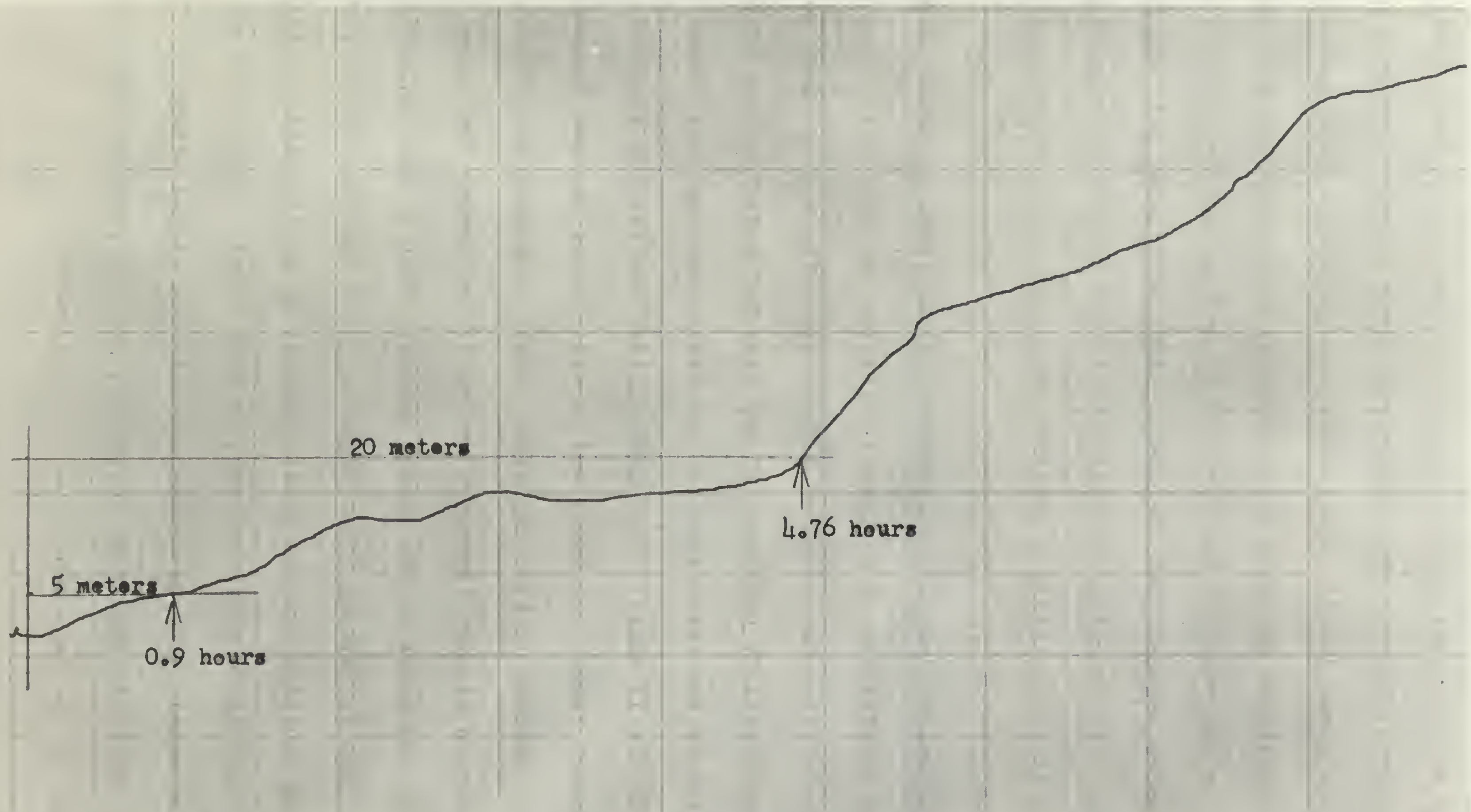
4.7°/unit

Frequency Locked System

Step Response

Figure 6.4

frequency hold for more than a very few hours. An electro-mechanical servo system might be able to improve this operator-null method. The importance of starting at exact frequencies cannot be over stressed. Once this has been accomplished, however, there is still the oscillator drift problem; these drifts are inherent in all crystal oscillators. The results of these tests are very similar to the phase comparison run described in the oscillator section; an approximate error due to drift of 0.2 usec (150 m) per day. After six tests it took an average of 1.22 ± .95 hours to produce a drift error of ± 5 meters, and 3.22 ± 1.5 hours to produce an error of ± 20 meters. Figure 6.5 is the fourth run. This is satisfactory for most cases over a short period of time, but any uses over a more extended period of time are going to require more stable oscillators.



Scale: 1"/hr

1.95 m/unit

System Run #4

Figure 6.5

7. Summary and Recommendations.

The receiver designed for this paper has proved to be satisfactory in all the tests that were run. It has yet to receive signals from an antenna, however this should not prove to be too great a problem. It has shown itself to be stable enough to withstand normal temperature variations and shock, and the test circuit allows for rapid field checks and possible readjustment of any deviations. The frequency locking system proposed for the master-slave oscillator pair has proved successful. The long-time holding circuit for the receiver oscillator works, but it is certainly a possible source of error and subject to improvement.

Recommendations for improvement of the receiver center around the proven feasibility of increased filtering and gain. At least one more crystal filter can be added without producing a great deal more temperature stability problems; in any case not more than can be compensated for by the test circuit. The best place for this filter would be early in the IF stage. Very good filters are readily available in this frequency range (500 KHz), and it will filter the sum frequency of the mixer. Another IC type amplifier should accompany the filter, while the gain should also be increased in the RF to improve the signal sensitivity. It was found in the tests, however, that it was desirable to lower the gain for strong input signals. This was done in the present receiver by shorting out the final stage of RF amplification. Either an AGC circuit could be introduced, or more simply a series of switches to vary the sensitivity to correspond with the signal strength. The filter in the front-end seems advisable, but the present crystal should be replaced by one less sensitive to its harmonics.

The obvious system recommendations are for atomic standards, if long duration runs are expected, and the master-slave relationship discussed in the appendix. For some uses the present oscillators are more than sufficient, but if this system should become widely accepted and used it would certainly be worth while to operate the shipboard receivers and retrievable master transmitters with more expensive, but more stable, atomic standards. An improvement in long term stability by a factor of 10, means an equal improvement in accuracy. The price can be compensated, to some extent, by using less expensive oscillators, with reduced long term stability, in the slaves.

The system presently satisfies the initial short term requirements; the recommendations should improve the long term situation.

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APPENDIX

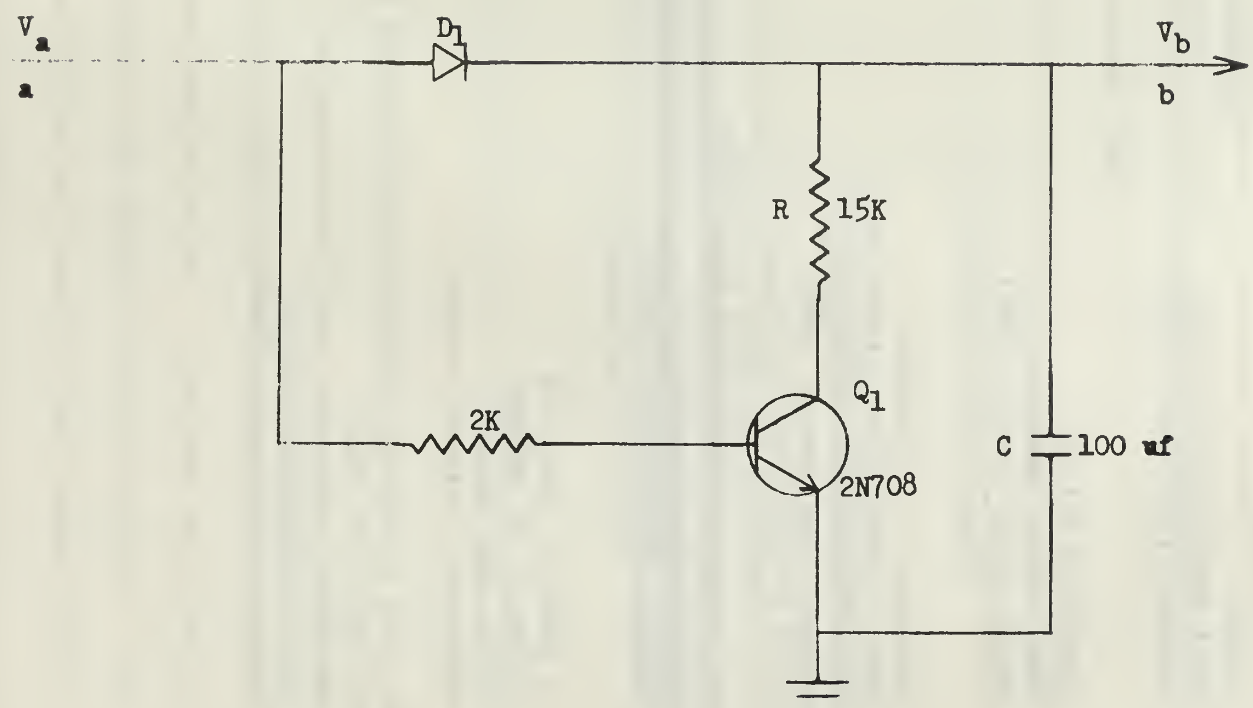
A Recommendation for a Multi-Transmitter, Time-Multiplexed, Frequency-Locked System.

In the introduction it was mentioned that more than one transmitter would be necessary for position plotting. It was also shown that the oscillators could be frequency-locked, through a local feedback loop, to a master. The addition of a receiver, similar to the one proposed in this paper, to a transmitter system will allow its oscillator to be slaved to the master without a physical connection. This, of course, can be done to as many transmitters as are necessary for the desired job. There are two decided advantages to this method. First, and most important, all the transmitter oscillators are at exactly the same frequency, and will therefore have the same drift rate with respect to the receiver oscillator. This means that the receiver oscillator, once aligned with one, is in alignment with all the others. Secondly it becomes economically feasible to consider the use of atomic standards, since only one transmitter, the master, would be required to have one. And in some cases it could be shore based to reduce the possibility of loss.

The obvious problem now arises of how to differentiate between transmitters, if all are at the same frequency. There are two possible solutions. Some method of AM coding is theoretically possible, but not recommended because of the desire for an extremely narrow bandwidth. The other solution, and recommended here, is a method of time sharing. Each transmitter would transmit a certain period of time, while the others are off. Since accurate oscillators are available at all stations they can be used as clocks, with both the order of transmission, and length of transmission, designating the transmitter. Periods of the order of 5 - 10 seconds are considered here to reduce the effect of pulsing on the frequency spectrum.

The next problem is how to keep the slave on frequency when the master is not on the air. The problem can be narrowed down to how to hold the oscillator varicap voltage at the same value it was when the oscillator was 'locked' on to the master. Figure I.1 proposes a 'fast attack - slow release' type holding circuit to be inserted in the feedback loop at the varicap terminals. The component values are only approximate, and should be determined to correspond with the pulse rate and duty cycle. If the voltage at point 'a' is greater than at 'b', D_1 and Q_1 will be forward biased and capacitor C will charge up to V_a (neglecting junction voltages) with a time constant equal to the product of the output impedance of the phase detector, in parallel with R, and the capacitor. If V_a is less than V_b, but not zero, D_1 will be back biased; Q_1, however, will be on, and C will discharge, through R, until V_b equals V_a, and D_1 conducts. When the master is not transmitting V_a equals zero, D_1 is back biased, and Q_1 is off. The capacitor will hold its voltage, for the off time, at V_b since the varicaps are a very large dc impedance. It was found that a 100 uf capacitor held the frequency exactly on for 35 seconds. Large changes will not occur in V_b since there is no position change and the drift rates are small.

A complete system test has not yet been run on this proposal, however all recommended procedures and circuits have been tested and shown feasible.



'Fast Attack - Slow Release' Holding Circuit

Figure I.1

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13. ABSTRACT

A precise navigation system has been proposed for use in mine and amphibious warfare. It is a continuous-wave phase comparison system, which derives its information from the change in phase between two stable oscillators as the distance between them is varied. A receiver, with very good phase versus temperature stability, was designed for this system. A test circuit was designed to field monitor any receiver phase changes which do occur. A method to frequency lock several oscillators to a master was also devised. Tests were run to determine the stability of the receiver, and the feasibility of the system.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Continuous-wave, Short-range, Precise Navigation System						
Phase Coherence						
Phase Stability						
Phase Comparison						
Schmitt Trigger: High Impedance, Stable Level						
Phase Locked, Voltage Controlled, Oscillators						